Flux dependent 1.5 MeV self-ion beam-induced sputtering from gold nanostructured thin films

J Ghatak, B Sundaravel, K G M Nair and P V Satyam

1 Institute of Physics, Sachivalaya Marg, Bhubaneswar 751005, India
2 Material Science Division, Indira Gandhi Center for Atomic Research, Kalpakkam 603 102, India
E-mail: satyam@iopb.res.in

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Abstract
We discuss four important aspects of 1.5 MeV Au\textsuperscript{2+} ion-induced flux dependent sputtering from gold nanostructures (of an average size of \(\approx 7.6 \text{ nm}\) and height \(\approx 6.9 \text{ nm}\)) that are deposited on silicon substrates: (a) the Au sputtering yield at the ion flux of \(6.3 \times 10^{12} \text{ ions cm}^{-2} \text{ s}^{-1}\) is found to be \(\approx 312 \text{ atoms ion}^{-1}\), which is about five times the sputtering yield reported earlier under identical irradiation conditions at a lower beam flux of \(\approx 10^9 \text{ ions cm}^{-2} \text{ s}^{-1}\), (b) the sputtered yield increases with increasing flux at a lower fluence and reduces at a higher fluence (\(1 \times 10^{15} \text{ ions cm}^{-2}\)) for nanostructured thin films while the sputtering yield increases with increasing flux and fluence for thick films (27.5 nm Au deposited on Si), (c) the size distribution of sputtered particles has been found to vary with the incident beam flux showing a bimodal distribution at a higher flux and (d) the decay exponent (\(\delta\)) obtained from the size distributions of the sputtered particles showed an inverse power-law dependence ranging from 1.5 to 2.5 as a function of the incident beam flux. The exponent values have been compared with existing theoretical models to understand the underlying mechanism. The role of wafer temperature associated with the beam flux has been invoked for a qualitative understanding of the sputtering results in both the nanostructured thin films and thick films.

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

1. Introduction

Nanostructures and nanoparticles are grown by various physical methods such as molecular beam epitaxy, pulse laser deposition and sputter coating. The sputter coating method involves the use of energetic particles (atoms or ions) bombarding the target of interest. During the sputtering process, the sputtered atoms or clusters generated due to the incident ion beam impingement condense on the surface of the specimen to be coated. Such processes are the basis of many thin film growth technologies (such as dc magnetron or RF sputtering) [1]. Energetic ion beams have also been utilized in synthesizing and modifying nanostructures [2]. Ion irradiation being an athermal process, properties of nanomaterials could be tailored, which are otherwise difficult by conventional methods [3].
from Sigmund and co-workers [10] with a modified thermal spike model. A qualitative hydrodynamical model with an anisotropic velocity distribution [11, 12] and fluid dynamical analysis [13] was also proposed to explain nonlinear sputtering. MD (molecular dynamics) simulations [14–18] have also been used to study the sputtering phenomena. MD simulation study of sputtering of self-ion induced Au and Cu targets at keV energies clearly revealed the non-linearity in sputtering [15].

The sputtering studies show a monoenergetically decreasing yield distribution, which closely follows inverse power-law decay:

\[ Y(n) = n^{-\delta}, \tag{1} \]

where \( n \) is the number of atoms present in the sputtered cluster. The shock wave model predicts the value of the exponent \( \delta \) to be equal to 5/3 or 7/3 [19]. In an experiment involving 400 keV Au in the Au film, Rehn et al [20] obtained the value of \( \delta \) to be around 2 for \( n \geq 500 \) and found it to be consistent with the shock wave model [19]. This value of \( \delta = 2 \) is consistent with the mechanism that large clusters are produced when shock waves, generated by subsurface displacement cascades, ablate the surface (the shock wave model). Recently, MD simulations have been carried out to study the effect of 100 keV Au bombardment on the Au nanocluster of size 8 nm [17]. The results of the above MD simulation show a distribution of emitted clusters \(( n \leq 100)\). Smaller clusters (up to \( n \sim 10 \)) show an inverse power law with \( \delta = 2.33 \). This was explained in terms of the thermodynamic equilibrium description [21], which predicted that the value of \( \delta \) lies between 2 and 7/3. For larger clusters the value of \( \delta \) is found to be higher than 7/3. These studies show the availability of various mechanisms for understanding the sputtering process.

Most of the reported experimental studies have been carried out on thick targets (i.e. not on nanostructured thin films) and in the low keV energy regime. Recently, sputtering from the nanostructured Au films deposited on the Si substrate has been investigated experimentally [22–26]. But no effort was made to study the power-law dependence of \( Y(n) \). In one of our previous studies [25], the power-law dependence of the emitted larger particles \( ( n \geq 1000) \) from Au nanostructures on silicon substrates due to MeV Au-ion bombardment at a low ion flux condition \(( 1.3 \times 10^{13} \text{ ions cm}^{-2} \text{ s}^{-1}) \) was reported. In this study, the decay exponent was found to be \( \approx 1.0 \) [25].

In this paper, we show that for the case of nanostructured thin films, the sputtering yield \( Y \) increases with the increase in the incident flux at a lower fluence \(( 6 \times 10^{13} \text{ ions cm}^{-2}) \) and reduces with the incident flux at a higher fluence \(( 1 \times 10^{15} \text{ ions cm}^{-2}) \). These results are compared with the sputtering from thick films. The role of the morphology at the surface and interfaces under different incident flux conditions in the sputtering yield and the size distribution of the sputtered particles is discussed. At high flux conditions, the transient wafer temperature would be higher and hence would play a role in the sputtering process.

2. Experimental

Au films of thicknesses 2.0 and 27.5 nm were deposited by a resistive heating method in high vacuum conditions (\( \approx 4 \times 10^{-6} \text{ mbar} \)) and at room temperature on \( \approx 2 \text{ nm} \) thick native oxide covered Si(1 1 1) substrates. Deposition rates for all samples were 0.01 nm s\(^{-1} \) and 0.1 nm s\(^{-1} \) for 2 nm and 27.5 nm thick Au films, respectively. Irradiation was carried out with 1.5 MeV Au\(^{2+} \) ions at room temperature with incident ion beam flux values of \( 3.2 \times 10^{10} \text{ ions cm}^{-2} \text{ s}^{-1} \), \( 6.3 \times 10^{11} \text{ ions cm}^{-2} \text{ s}^{-1} \) and \( 6.3 \times 10^{12} \text{ ions cm}^{-2} \text{ s}^{-1} \) (hereafter these conditions will be referred to as low flux (LF), medium flux (MF) and high flux (HF), respectively). The fluences on the samples were varied from \( 6 \times 10^{11} \) to \( 1 \times 10^{15} \text{ ions cm}^{-2} \). The substrates were oriented 5° off normal to the incident beam to suppress the channelling effect. The irradiation at a flux of more than \( 1.3 \times 10^{15} \text{ ions cm}^{-2} \text{ s}^{-1} \) was carried out with the 1.7 MV accelerator facility at the Indira Gandhi Center for Atomic Research, Kalpakkam. Irradiation with a beam flux of less than \( 1.3 \times 10^{15} \text{ ions cm}^{-2} \text{ s}^{-1} \) and Rutherford backscattering spectrometry (RBS) has been performed using 3 MV accelerator facilities using a surface barrier detector of a resolution of 35 keV. All the irradiation was carried out using a raster scanner to have uniformity of irradiation. During the irradiation, the sputtered particles were collected on carbon-coated copper grids (catcher grid) kept \( \approx 1 \text{ cm} \) above the sample, with a geometry as shown in figure 1(a). Care has been taken to have identical geometry for the collection of sputtered particles. RBS measurements with 2 and 3.0 MeV He\(^{2+} \) ions were used to determine the variations in the effective film thicknesses of Au films before and after irradiation. Transmission electron microscopy (TEM) measurements were performed (using JEOL JEM-2010 operating at 200 kV) for the substrates before and after irradiation and on the catcher grids. Planar and cross-sectional TEM (XTEM) samples have been prepared using mechanical polishing followed by ion milling with 3.5 keV Ar ions.

3. Results and discussions

The irradiation experiments have been performed on Au nanostructured thin films of effective thickness \( \approx 2.0 \) and 27.5 nm thick gold films, deposited on the Si(1 1 1) substrate. The effective thickness has been determined with the SIMNRA simulation package [27] using the bulk Au density. In the RBS simulation (using SIMNRA), parameters such as detector energy resolution and energy calibration values have been determined with the standard samples using bulk Si and a thick Au film. For fitting the backscattered peak from Au, the bulk density has been used and then the effective thickness was determined in units of atoms cm\(^{-2} \) (termed as areal density). With these fixed parameters, the RBS spectra of nanostructured thin films have been fitted using bulk Au density to obtain the area under the gold peak, which was used to determine the effective thickness. The sputtering yield was then obtained by dividing the areal density with the fluence. It should be noted that the surface and interface roughness do not affect the value of the overall area under the curve and hence do not affect the value of the areal density. Prior to irradiation, the substrates were analysed using planar and cross-sectional TEM. Figures 1(b) and (c) represent bright field planar and XTEM images of the pristine sample. Both figures 1(b) and (c)
show isolated Au islands that have been grown on the Si substrate (such thin films are termed as nanostructured thin films). Figures 1(d) and (e) represent the histograms of the lateral size (from several frames such as figure 1(b)) and height distribution (from several frames such as figure 1(c)) of the Au nanostructures present on the Si surface. A Gaussian fit of the respective histogram gives the average Au nanostructure lateral size $\approx 7.6 \pm 1.5$ nm and the average height $6.9 \pm 0.8$ nm. Surface coverage for these nanostructured samples is found to be $\approx 40\%$. Figure 1(f) depicts bright field XTEM micrographs of a 27.5 nm thick gold film deposited on silicon. The thicknesses of the Au films measured from both the RBS and TEM are in good agreement. It is evident from the cross-sectional micrographs that a $\approx 2.0$ nm thick native oxide was present at the interface of the gold films and the substrate. We present the detailed results on various aspects of sputtering from nanostructures in the following.

3.1. Sputtering yield measurements

Figure 2(a) shows the RBS spectra obtained from the nanostructured Au films on Si targets before and after irradiation with 1.5 MeV Au$^{2+}$ at a fluence of $6 \times 10^{13}$ ions cm$^{-2}$ using the different flux values of $3.2 \times 10^{10}$ ions cm$^{-2}$ s$^{-1}$, $6.3 \times 10^{11}$ ions cm$^{-2}$ s$^{-1}$ and $6.3 \times 10^{12}$ ions cm$^{-2}$ s$^{-1}$ (LF, MF and HF conditions, respectively). From the RBS measurements, the reduction in the film thickness was found to be 32%, 42% and 48% in LF, MF and HF conditions, respectively, in comparison with the pristine sample. The RBS measurements clearly indicate that with the increase in the incident beam flux, the sputtering (reduction in the amount of Au on the substrate) also increases. From the RBS data of the irradiated nanostructured Au films corresponding to a fluence of $6 \times 10^{13}$ ions cm$^{-2}$, the sputtering yield was found to be as high as 125 atoms per ion for the HF condition, while the yield values were 107 and 95 atoms per ion corresponding to the MF and LF conditions. However, the above sputtering yields were underestimated as the coverage of the Au islands was only 40% in the pristine film. By taking the coverage into account, the yields were found to be 237, 267 and 312 for LF, MF and HF conditions, respectively. Figure 2(b) shows the RBS spectra obtained from the nanostructured targets before and after irradiation with 1.5 MeV Au$^{2+}$ at a higher fluence ($1 \times 10^{15}$ ions cm$^{-2}$) as a function of the incident flux. At this high fluence, the reductions in the film thicknesses were found to be 94%, 64%
The reduction in the thickness increases with the increase in the beam flux for a thick target, which is similar to that as seen in figure 2(a). The yield for the thick film has also been calculated in a similar manner as observed for nanostructure film systems and the corresponding sputtering yield values at MF and HF conditions are 144 and 340, respectively.

Table 1 shows some of the sputtering yield data available in the literature (theoretical, simulated and experimental) and from this work for 1.0–2.5 MeV self-ion-induced sputtering from gold films. Among the existing theories on nonlinear sputtering, the shock wave model based on hydrodynamical analysis [11, 12] fits well with many of the experimental results. But the theory gives an overestimated sputtering yield at energies of more than 1.0 MeV. Most of the experimental work has been carried out at low flux and fluence to avoid cascade-overlapping and prominent nonlinear effects.

It should be noted that this work is different from the others in two aspects: (a) sputtering from nanostructures and (b) sputtering as a function of flux (low to high flux conditions). From table 1, it is evident that a sputtering yield of about 70 was observed from previous experimental observations [6–8]. This value is about five times less than the sputtering yield observed for high incident beam flux conditions both for nanostructured and for continuous gold films for 1.5 MeV incident ions. It is to be noted that the sputtering yield for both types of targets came out to be comparable at the HF condition, whereas the sputtering yield at a lower flux is less in thick films compared with nanostructured films.

Recent studies by the group of Baranova et al. showed large sputtered yields for nanodispersed targets with Au$_5$ cluster ions with an energy of 200 keV atom$^{-1}$ (LF, low fluence and nuclear energy loss dominant regime) [23], whereas, under similar irradiation conditions (i.e. with cluster ions), the sputtering yield from bulk gold targets was found to be less compared with nanodispersed systems [7]. Interestingly, the sputtering yield calculated from SRIM [28] is 27 (as mentioned in table 1) which is low compared with the sputtering yield ($\approx$48) calculated from Sigmund’s linear theory [4] for 1.5 MeV Au $\rightarrow$ Au. SRIM results also show a lower yield for thinner films in contradiction to the recent experimental results [23, 24]. Though it is true that sputtering phenomena are significantly dominated in the nuclear energy loss regime, recent studies show that the contribution of electronic energy
loss to the sputtering yield is prominent [26, 29]. In this work, the ratio of electronic to nuclear energy loss is 0.26 for 1.5 MeV Au²⁺ in the Au target, i.e. electronic energy loss contributes 21% to the total energy loss and hence should not be neglected in the sputtering calculation.

The prominent variation in sputtering for nanostructured films and thick films at a high fluence (1 × 10¹⁵ ions cm⁻²) and HF condition is due to the variation in ion-beam-induced interface mixing in Au/Si systems. To understand the surface and interface morphology in irradiated systems XTEM measurements have been carried out. Figure 3(a) depicts a XTEM micrograph of the nanostructured target after irradiation at a fluence of 1 × 10¹⁴ ions cm⁻² under LF condition. From this figure, it is evident that no interface mixing has taken place. We can also infer that no interface mixing takes place for a fluence of less than 1 × 10¹⁴ ions cm⁻² under LF and normal incident conditions (5° impact angle). At the HF condition, an unusual mass transport from the nanostructured film was found to be present. More details of the mass transport under the HF condition have been discussed elsewhere [30, 31]. Figure 3(b) shows a XTEM bright field micrograph of the nanostructured target after irradiation at a fluence of 1 × 10¹⁴ ions cm⁻² irradiated at HF condition. The inset of figure 3(b) shows a high resolution (HR) lattice image from a region shown in the circle in figure 3(b). From this figure, it is clear that Au atoms from the nanostructures on the Si surface have been transported to the interface and reacted to form gold silicide. The HR lattice image shows a spacing of 0.305 ± 0.005 nm. As the Si substrate has already amorphized and no gold d-spacing matches with this value, we concluded that a metastable gold silicide (Au₅Si₂) has been formed [30]. Figures 3(c), (d) and (e) show XTEM images of the irradiated nanostructured system after irradiation at a fluence of 1 × 10¹⁵ ions cm⁻² under LF, MF and HF conditions, respectively. At this fluence, a very large amount of material has been sputtered out at the LF condition. This is consistent with the 94% reduction in RBS spectra (as shown in figure 2(b)). At the fluence of 1 × 10¹⁵ ions cm⁻² and under the HF condition, surface craters and interface mixing have been observed (figure 3(e)). Unlike the absence of a large amount of Au at the surface in the case of the LF condition, there appears to be more Au available for sputtering at the interface. The presence of craters may also play a role in the reduction of sputtering. At the MF condition, there is more material present on the surface when compared with both LF and HF conditions. Under similar conditions, irradiation effects from thick film have also been studied and depicted in figure 3(f). Figure 3(f) shows a XTEM image of a thick film after being irradiated at a fluence of 1 × 10¹⁴ ions cm⁻² under the HF condition. It is to be noted that at LF, no interface mixing has been observed for thick films [32], while at the HF condition mass transport across the interface is evident from figure 3(f). Even though mass transport across the interface has been observed for the thick film under the HF condition, there is enough Au material present on the surface and hence more sputtering at higher fluence has been observed. But this is not the case for the nanostructured target. It is expected that the embedded Au has a lower sputtering yield due to dilution and the small area surface. At high fluence conditions, as the whole amount of Au at the surface has been sputtered (also for LF conditions), very little sputtering could be seen. In other words, the lack of surface Au leads to a slowing down of the sputtering in the case of HF and high fluence irradiation conditions.

It is clear from the above experimental observations that the incident ion beam flux plays an important role in the sputtering process. In the following, the role of the HF condition in terms of the rise in the transient wafer temperature has been discussed. As given by Nakata’s formalism [33], the wafer temperatures have been calculated for the fluxes during irradiation (a detailed calculation has been reported elsewhere [30]). At the highest flux used in this study (i.e. 6 × 10¹³ ions cm⁻² s⁻¹) and for the fluence of 6 × 10¹³ ions cm⁻², the temperature calculated using the prescription of Nakata would be 1125 K (for an irradiation time of 9 s). Following the above calculations, for the fluence 6 × 10¹³ ions cm⁻² at a flux of 6.3 × 10¹¹ ions cm⁻² s⁻¹, the temperature would be 650 K (irradiation time: 90 s) and the wafer temperature would be 400 K (irradiation time: 460 s) for 1.3 × 10¹¹ ions cm⁻² s⁻¹. This means that at the same fluence, the temperature of the wafer during irradiation is higher for the higher beam flux. As the wafer temperature increases, the heat of sublimation (∆H) of Au decreases and hence the binding energy also decreases. It has already been established that the sputtering yield is inversely proportional to the binding energy [4, 34]. Hence, a rise in the wafer temperature results in the enhancement of the sputtering cross-section. Sigmund and Szymonsky [35] reviewed the temperature-dependent scenario up to that period and theoretically predicted that the high temperature regime (thermal spike) yields little variation in the sputtering yields. But the experiments and simulation studies byBehrisch et al showed a drastic Ag sputtering yield enhancement with
increasing target temperature during irradiation [34]. Increase in sputtering (as long as enough material is present) on the substrate in both thick and nanostructured Au films at fluence and at the HF condition has been attributed to the wafer temperature.

3.2. Sputtered particle size distribution

The sputtered particle size distribution as a function of the beam flux is discussed below. The sputtered particles have been collected (geometry is shown in figure 1(a)) on a carbon-coated grid. Figures 4(a), (b) and (c) show the TEM micrographs of sputtered Au particles collected on the catcher grid at the LF, MF and HF conditions respectively, at a fluence of $6 \times 10^{13}$ ions cm$^{-2}$. Figures 4(d), (e) and (f) show the corresponding size distributions of sputtered particles whose TEM data have been shown in figures 4(a), (b) and (c), respectively. To give quantitative information about the sputtered particles, we have fitted the particle size distribution with the log-normal distribution which is given by

$$f(x) = \frac{1}{\sqrt{2\pi}wx} \exp\left(-\frac{(\ln(x/x_c))^2}{2w^2}\right), \quad (2)$$

where $x_c$ and $w$ are the most probable size and width of the size distribution, respectively. This is because the distribution of nanoparticles is often found to be a log-normal distribution [36]. The average particle size was found to be $7.7 \pm 0.3$ nm and $9.5 \pm 0.2$ nm for samples in the LF and MF conditions (figures 4(d) and (e)), respectively. Interestingly, a bimodal distribution has been found in the HF irradiation condition (as shown in figure 4(f)) with average particle sizes of $3.4 \pm 0.3$ and $10.0 \pm 0.2$ nm. It is also to be noted that the width ($w$) of the distribution is minimum under the HF irradiation condition. At a higher fluence ($1 \times 10^{15}$ ions cm$^{-2}$) under HF conditions also a bimodal distribution of sputtered particles for the same system has been observed [37]. The origin of the bimodal distribution has been explained as follows: at flux and fluence values of $6 \times 10^{12}$ ions cm$^{-2}$ s$^{-1}$ and $6 \times 10^{13}$ ions cm$^{-2}$, Au islands reacted with Si and formed gold silicide at the interface [30]. This means that, at a higher beam flux, the Au islands on the Si undergo ion beam mixing and form a silicide phase, whereas at a lower beam flux at this fluence, no ion beam mixing takes place across the interface. At the initial conditions of irradiation, the availability of gold material is greater compared with at a later stage (for the case of beam incidence on nanostructures). The size of the sputtered particle appears to be directly proportional to the amount available in the nanostructures. This results in sputtering of bigger clusters in the initial stages and smaller clusters in a later stage, giving rise to a bimodal distribution (as shown in figure 4(f)).
Figure 4. (Colour online) (a)–(c) Bright field TEM micrographs of sputtered Au nanoparticles which have been collected on catcher grids during irradiation of the nanostructured target (2 nm Au on Si) with 1.5 MeV Au$^{2+}$ at a fluence $6 \times 10^{13}$ ions cm$^{-2}$. (a)–(c) The ion beam flux of $3.2 \times 10^{10}$ ions cm$^{-2}$ s$^{-1}$, $6.3 \times 10^{11}$ ions cm$^{-2}$ s$^{-1}$ and $6.3 \times 10^{12}$ ions cm$^{-2}$ s$^{-1}$ with corresponding size distributions shown in (d)–(f), respectively. The histograms in (d)–(f) have been fitted with a log-normal distribution function (as mentioned in the text). The most probable size, $X_c$, and width, $W$, of the size distribution have been indicated in the figure.

3.3. Sputtering yield decay exponent ($\delta$)

The value of the decay exponent ($\delta$) would help in understanding the underlying mechanism of the sputtering process [20]. The sputtered particle size analysis has been carried out to determine the decay exponent [25]. Assuming a spherical nature for the sputtered particles, the distribution obtained using the particle size diameter has been converted into hemispherical volume distribution as given by Rehn et al [25]. Figure 5 shows the values of $Y(n)$ versus the hemispherical volume of the sputtered particles (which is directly proportional to the value of $n$). In figure 5, the legends S1, S2 and S3 correspond to the irradiated samples at the fluence of $6 \times 10^{13}$ ions cm$^{-2}$ in the HF, MF and LF conditions, respectively. To avoid overlap in plotting, S1, S2 and S3 were multiplied by factors 8.0, 1.0 and 0.25, respectively. The data points marked as S1, S2 and S3 were fitted with a straight line to obtain the $\delta$ values. For the hemispherical volume of more than 100 nm$^3$, a straight line fit (as shown in figure 5), $\delta$ values were found to be 2.0 ± 0.1 and 1.5 ± 0.1 for S2 and S3, respectively. Because of the bimodal distribution (figure 4(f)) for S1, we got two $\delta$ values, 1.6 ± 0.2 for particle sizes $\leq 5$ nm and 2.5 ± 0.2 for particle sizes $\geq 6$ nm. The average sputtered particle size is greater for sample S1 and hence faster decay takes place. The $\delta$ value for sample S3 is nearly the same as that reported earlier [25]. The shock wave model predicts the $\delta$ value to be 2 or 2.33 [19] and may be comparable to values from S1 and S2. If the shock wave mechanism is assumed to be the underlying mechanism, then the same $\delta$ values for the irradiation at varying beam fluxes would be expected. Thus, from the present data, it is clear that the sputtering mechanism is not the same at all incident ion beam fluxes. Though the shock wave model works for many experimental results [20, 38] under ion irradiation conditions at LF on thick continuous films, the model is not appropriate for studying the sputtering from nanostructured targets.

A proper reasoning for the different exponent values is difficult in the present experimental conditions due to the presence of complicated surface and interface morphology, mass transport and alloy formation across the interfaces, sublimation of nanostructures and multi-ion impacts [30]. The MD simulations of Kissel and Urbaske [17] showed
Figure 5. (Colour online) The log–log plot of hemisphere volume distribution. S1, S2 and S3 correspond to a fluence of $6 \times 10^{13}$ ions cm$^{-2}$ with a flux of $6.3 \times 10^{12}$, $6.3 \times 10^{11}$ and $3.2 \times 10^{10}$ ions cm$^{-2}$ s$^{-1}$. To avoid overlap, S1, S2 and S3 were multiplied by 8, 1 and 0.25. Straight solid lines are a linear fit to curves S1, S2 and S3 to get the decay constants ($\delta$) for each beam flux.

the sputtering from spherical Au clusters (radius $R = 4$ nm) due to 100 keV Au atom bombardment. For smaller cluster sizes $n \lesssim 10$, the data indeed follow a polynomial decay with $\delta \approx 2.3$. While comparing this result with the MD simulation study of 100 keV Au bombardment of the Au(1 1 1) surface (>12 000 atoms), the decay exponent comes out to be $\delta \approx 2.8$ [16]. From the above studies it can be inferred that large clusters are emitted in the case of a spherical island system with a higher probability than for planar solid surfaces. It also clearly indicates that the mechanism of sputtering from the nanostructured target is different from that from a solid surface (continuous layer). For a nanostructured target, sputtering was attributed to the thermodynamic equilibrium description [17] where cluster production from a volume energized to reach the critical point of the gas–liquid phase transition is known to lead to a cluster-mass distribution $\propto n^{-7/3}$ [21]. In our present experiments, only the decay exponent of samples irradiated at the highest flux, $6.3 \times 10^{12}$ ions cm$^{-2}$ s$^{-1}$, is close to the decay exponent of thermodynamic equilibrium description.

4. Conclusions

In conclusion, the present results show that the sputtering yield is affected by the incident ion beam flux. With the ion flux of $6.3 \times 10^{12}$ ions cm$^{-2}$ s$^{-1}$, the sputtering yield of Au from a nanostructured target due to 1.5 MeV Au ions has been found to be as high as 312 atoms ions$^{-1}$ which is comparable to the values for a thick continuous film. Our experimental data on the size of the sputtered particles at a given fluence with different beam flux values clearly show a strong influence of the ion beam flux on the sputtered particle size distribution. The decay exponent of the sputtering particles is also found to vary from $\approx 1.5$ to $2.5$ for the flux values from $3.2 \times 10^{10}$ to $6.3 \times 10^{12}$ ions cm$^{-2}$ s$^{-1}$ suggesting that the mechanisms operative at different flux values are different. The models that explain the mechanism of the sputtering phenomenon should take into account the beam flux effects. The higher sputtering at a higher beam flux has been attributed to the beam-induced transient temperature rise.

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