X-Ray Reflectivity Study of Gold Films
During Sputter-Deposition

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Abstract

We performed *in-situ* x-ray reflectivity measurements of gold films during sputter-deposition on polished silicon substrates. The measurements were performed at several substrate temperatures and under two argon pressures. The gold surfaces were also examined by scanning tunneling microscopy after deposition to obtain their real-space topographic images. These images were used to complement the x-ray reflectivity measurements in determining the effect of argon pressure on the gold surface and its height-height difference functions. An approximation for height-height difference functions was employed to analyze the x-ray reflectivity data. The measured interface width during growth follows a simple power-law behavior consistent with recently

developed dynamic scaling behavior. The scaling exponents, however, do not agree well with predictions based on some models in $2 + 1$ dimensions.

I. INTRODUCTION

The formation of rough interfaces plays an important role in fundamental processes currently of interest in many basic and applied scientific disciplines. Rough interfaces form in nature and in modern materials processing by the dynamic exchange of material at the interface in thermodynamic nonequilibrium conditions. Examples of such interface formation are numerous including surface/interface corrosion, vapor phase deposition, chemical deposition and dissolution, crystal growth and dissolution of minerals, biological growth, erosion of earth surface, and so forth. Therefore, attempt to find the fundamental laws governing the formation of such rough surfaces is certainly one of most challenging subjects in modern materials science and in physics. Since the formation of such rough interfaces is a nonequilibrium process, a conventional statistical mechanics approach is not applicable. However, it was recently realized, aided by computer simulations, that an evolving rough interface finally reaches a steady state. This steady state can be described by a general scaling approach based on concepts of scale-invariance and the fractal nature of rough interfaces [1].

Since then, numerous analytical and computational investigations were made to study the scaling natures of various models. While marked progress has been made in theoretical studies, there exists a much smaller number of experimental investigations of growing interfaces [?]. One of the reasons for this is the requirement of *in situ* examination of such interfaces without disrupting the growing interface itself. An experimental probe suitable for such *in situ* microscopic examination of a growing interface in a variety of special environments is the x-ray reflectivity (XR) technique. The x-ray reflectivity technique has been previously used for *in situ* examinations of various interfaces. Examples are molecular beam epitaxy on semiconductor interfaces in ultra high vacuum environments [6], electrochemical corrosion [7], and crystal growth and dissolution of minerals in contact with aqueous fluids [8].

In this paper we use the x-ray reflectivity technique to *in situ* investigate the kinetic

roughening of an interface formed by sputter-deposition from a vapor phase under nonequilibrium conditions. A part of this work has previously been published elsewhere [9]. Gold was deposited from a vapor onto clean, polished silicon by sputter deposition. The polished silicon provides a nearly ideal 2-D planar substrate; sputter deposition was chosen because of its wide use in industrial deposition processes. Scanning tunneling microscopy (STM) was additionally used for the examination of the gold surface after deposition. The aim of this work is two-fold: 1) to determine if the interfacial width exhibits dynamic scaling behavior during sputter deposition, and if so to determine the exponents associated with the scaling behavior, and 2) to investigate the effect of deposition conditions on the scaling exponents and on the nature of interfacial inhomogeneities both lateral to and normal to the substrate surface.

II. GROWTH MODELS AND SCALING BEHAVIORS

One of the earliest important developments in understanding kinetic roughening during growth is from a computational study by Family and Vicsek [10]. The central result of the computer study, using the Eden [11] and the ballistic aggregation [12] growth models, is a postulation of scaling behavior,

$$W(L, t) \sim L^\chi f(t/L^{\chi/\beta}) \quad (1)$$

where $W(L, t)$ is the root-mean-square (rms) width of the interface at time t , and L is the size of the substrate. The function $f(x)$ has the behavior, $f(x) \approx x^\beta$ for $x \ll 1$, and $f(x) = \text{constant}$, for $x \gg 1$. The symbols χ and χ/β are the finite-size scaling exponent and the dynamic scaling exponent, respectively.

Numerous recent theoretical studies are focused on the study of the scaling behavior for various sets of growth rules. Another group of theoretical studies takes an analytical approach by solving various forms of the Langevin equation. A simple linear Langevin equation has been studied by Edwards and Wilkinson [13]. Later the lowest-order nonlinear

Langevin equation was studied by Kardar et al. [14]. The nonlinear equation and more complicated forms of linear Langevin equations including higher order derivatives were also studied by employing so called solid-on-solid models [15,16] where continuum equations are considered on lattices.

Throughout this paper we will assume that we can describe a surface as a single valued function $h(\vec{x}, t)$. This assumption is valid for our experimental condition since we find that the density of sputter-deposited gold films is nearly that of bulk. Then the time dependence of $h(\vec{x}, t)$ can be described by a Langevin equation as an expansion in its local derivatives [17].

$$\begin{aligned} \frac{\partial h}{\partial t} = & \nu \nabla^2 h - \nu_1 \nabla^4 h + \lambda (\nabla h)^2 + \lambda_1 \nabla^2 (\nabla h)^2 \\ & + \text{higher order terms} \cdots + \eta(\vec{x}, t) \end{aligned} \quad (2)$$

where $\eta(\vec{x}, t)$ is a Gaussian white noise in the surface dimension d_s and in time. For clarity we will denote $d = d_s + 1$ for the spatial dimension, $\vec{r}$ for a vector in d dimensions, $\vec{x}$ for a vector in d_s dimensions. The simplest case of this Langevin equation is when all ν 's and λ 's are zero. This is the case for growth in a completely random manner by the noise term only. For completely random growth an arriving atom sticks at the first site it hits and no diffusion of the atom is allowed. This is a trivial case since each point on the surface will be completely independent and follow the well known Poisson statistics. That is,

$$W = h^{\frac{1}{2}} \quad (3)$$

The exponents for this case are $\chi = \infty$ and $\beta = 0.5$ independent of the dimensionality. The next simplest case is when $\nu \neq 0$ but all other terms are zero. Since this term is proportional to the negative local curvature of the interface, it relaxes the hills and valleys. This case is known as Edward and Wilkinson's model. Fourier analyses can be done for this case and the exact values of the exponents have been obtained [13]. The exponents are $\chi = (3-d)/2$ and $\beta = (3-d)/4$. In particular, for 2+1 dimensions χ and β are zero and the rms width shows a logarithmic divergence in time and in size. The atoms are allowed to move instantaneously

to maximize their coordination numbers and the surface reaches its complete relaxation. When all but ν_1 are zero, analysis shows that the exponents χ and β are $(5 - d)/8$ and $(5 - d)/2$, respectively [17]. In this case the arriving atoms can move to maximize their in-plane coordinate number and lead to an incomplete relaxation of the surface. When the nonlinear terms are included in the equation, the analytical treatment becomes more complex but a few specific cases have been studied. The most popular case is when both ν and λ are not zero. This case is generally known as the KPZ equation [14]. Many growth models studied so far fall into the universality class of the KPZ equation. The KPZ equation successfully describes many different growth processes such as the Eden model and ballistic deposition. Renormalization group (RG) analysis was used to find that the exponents χ and β are $1/3$ and $1/2$, respectively, for $1 + 1$ dimensions. The KPZ nonlinear term, $(\nabla h)^2$, does not appear for a current conserving process (no evaporation and vacancies) and the other nonlinear term in Eq. (2) was suggested to be relevant for MBE growth processes [17]. An equation keeping only two terms ($\lambda_1, \nu_1 \neq 0$) was proposed to describe MBE processes and the RG analysis shows that the exponents χ and β are $(5 - d)/3$ and $(5 - d)/(7 + d)$, respectively.

III. EXPERIMENTAL DETAILS

The x-ray reflectivity measurements were performed *in-situ* by using a high vacuum chamber equipped with a faced-magnetron sputtering system and x-ray transparent windows. Details of the chamber are presented elsewhere [18], and only a brief account will be given here.

The experimental geometry is shown in Fig. 1. The axial magnetic and radial electric fields ionize Ar gas and accelerate the positive Ar ions at the targets with sufficient energy (200-450 eV) to remove (sputter) neutral gold atoms. The sputtered gold atoms form a homogeneous "cloud" and deposit onto the substrate. The substrate is located at right angles to the two faced targets, which were kept approximately 5 cm apart, and positioned

to remain well below the edge of the plasma. The gold targets were 0.8 mm thick and 2.5 cm in diameter. The base pressure of the chamber was approximately 1×10^{-5} Torr. Research grade Ar gas was used for sputtering and gas flow was controlled by a needle valve and 50 l/s turbomolecular pump. The Ar gas pressure was held at either 1 or 10 mTorr during deposition as measured by a convectron pressure gauge. A low current (0-20 mA) variable voltage power supply (0-3000 V) was used to power the faced magnetron sputtering gun and was interfaced to a personal computer. The gun was operated at 300-450 V and the gold deposition rate was 0.5-1 Å/s. The gold deposition rate was accurately determined for each series of XR scans.

The substrates were polished silicon (1.3 cm by 1.3 cm by 0.15 cm) prepared by successive ultrasonic cleaning for five minutes each in research grade acetone, ethanol, and distilled water. The substrates were then blown dry using pressurized nitrogen gas and mounted onto a heating or cooling sample block with highly conductive silver cement. X-ray reflectivity measurements indicated that the silicon surfaces were contaminated with a hydrocarbon-like layer approximately 20 Å thick even after a careful cleaning procedure. The contamination was easily removed in most cases by baking to 500 K under 10^{-5} Torr vacuum. The XR scans with and without baking are shown in Fig. 2. The upper scan (filled circles) is without baking the sample and the lower scan (open circles) is after the baking to 500 K for a half an hour. Detailed discussion of fits to these scans is deferred to Sec. IV E. The XR indicates that we do remove a hydrocarbon-like layer from the surface and that the native silicon oxide has almost identical electron density to the silicon itself (Silicon oxide does desorb at much higher temperature). The density of silicon oxide is known to be very close to that of silicon but Fig. 2 shows the oxide on Si(111) surface is actually compact without any voids. Therefore, we needed not attempt to remove the native SiO₂ layer. Resistive heating was used to heat the sample block above room temperature, and a flow-through liquid nitrogen scheme was used to cool to 220 K. The sample temperature was stabilized to better than ± 0.5 K.

The x-ray measurements were performed at the National Synchrotron Light Source on

beamline X22B. The incident beam was focused in the horizontal and vertical directions by a toroidal nickel-coated aluminum mirror. The incident beam spot size was ~ 2 mm horizontal by ~ 1 mm vertical. A single flat Ge(111) crystal monochromator was used and the incident x-ray wavelength was $1.50 \text{ \AA}$. The measurements were performed in the horizontal scattering geometry and the instrumental resolution was approximately $1 \times 10^{-3} \text{ \AA}^{-1}$. The chamber was mounted onto the phi circle of a four-circle diffractometer and scintillation detectors were used to monitor the incident and reflected x-ray beam intensities. While recording XR data the power supplied to the faced-magnetron gun was reduced such that the amount of gold deposited during data acquisition was negligible but at the same time keeping the plasma active throughout the measurement. A gold "buffer layer" between 50 and $75 \text{ \AA}$ thick was deposited at $T = 300 \text{ K}$ and $P_{\text{Ar}} = 10 \text{ mTorr}$ before sputtering gold at desired deposition conditions. Series of XR scans were measured during deposition at $P_{\text{Ar}} = 1$ and 10 mTorr , and $T = 220, 300, \text{ and } 350 \text{ K}$. The Ar sputtering pressures were chosen such that gold particles incident on the gold substrate were either; 1) thermalized by collisions before deposition onto the silicon surface (10 mTorr) or 2) had large incident momenta and followed straight-line trajectories before depositing onto the silicon surface (1 mTorr). The substrate temperatures were chosen to investigate the possible effects of surface diffusion.

IV. RESULTS AND DISCUSSION

A. Review of Specular X-ray Reflectivity

The X-ray reflectivity technique has been widely used in recent years because of its simple interpretation and easy to obtain high-precision data at synchrotron x-ray sources. In this section we will derive the equation that we use for our specular (incident angle equals reflected angle and the plane containing the incident and reflected beam is perpendicular to the surface) XR data analyses. We make use of the usual definition of vacuum momentum transfer, $Q = 4\pi \sin \theta / \lambda = 2K \sin \theta$ and the scattering angle θ will not appear directly in

the equations. Specular XR measurements are made by monitoring changes in the reflected X-ray intensity as a function of Q . In this way changes in electron density across interface(s) are determined. As described in Sec. III, gold is deposited onto a polished silicon substrate. Therefore there are two interfaces in the system; the gold/vacuum interface and the gold/silicon interface as schematically shown in Fig. 3. In our case medium 1 is gold and medium 2 is silicon. The XR technique allows us to sensitively determine the width of these interfaces, the gold density, and the gold thickness.

In the x-ray limit, the dielectric constant, ϵ , is slightly less than one. That is, the electric susceptibility $\chi_e = \{1 - \epsilon(Q, \omega)\}/4\pi$ is much smaller than unity and can be written as [19,20],

$$\begin{aligned}\chi_e(Q, \omega) &= \{1 - \epsilon(Q, \omega)\}/4\pi \\ &= \frac{Ne^2}{m\omega^2} S(Q, \omega) \\ &= \frac{Ne^2}{m\omega^2} \sum_{m=0}^M \{F_1^m(Q, \omega) + iF_2^m(\omega)\} e^{iQ \cdot r} \\ &\simeq \{\delta(Q, \omega) + i\beta(Q, \omega)\}/2\pi\end{aligned}\tag{4}$$

where $S(Q, \omega)$ is the structure factor of the unit cell with M atoms in, N is the total number of unit cells in the system, and $F(Q, \omega) = F_1(Q, \omega) + iF_2(\omega)$ is the scattering factor, where the imaginary component is a result of photoelectric absorption. The index of refraction is usually defined as $n = 1 - \delta - i\beta$ [21].

For a *single*, flat interface the reflection amplitude can be calculated from the Fresnel formula of classical optics [19]

$$V^F = \frac{n_0 \sin \theta_0 - n_1 \sin \theta_1}{n_0 \sin \theta_0 + n_1 \sin \theta_1} = \frac{Q_0 - Q_1}{Q_0 + Q_1}\tag{6}$$

where n_0 and n_1 are the complex indices of refraction and Q_1 , $Q_1 = \sqrt{Q^2 - 4\pi\chi_1 K^2}$, is the momentum transfer inside medium "1". Q_1 can also be written in terms of a critical momentum transfer (Q_1^c) below which incident x-rays undergo total external reflection, namely, $Q_1 = \sqrt{Q_0^2 - Q_1^{c2} - i\left(\frac{4\pi}{\lambda}\right)^2 \beta_1}$. From Snell's law $Q_1^c \approx 0.0289 \sqrt{(Z_E/A_N)\rho_m}$ where Z_E is the

total number of electrons whose binding energy is less than the incident x-ray energy, A_N is the average atomic number of the material, and ρ_m is the mass density. For silicon and gold Q_1^c is 0.032 and 0.081 $\text{\AA}^{-1}$, respectively.

Real interfaces, however, are not ideally terminated, but are rough on length scales comparable to the x-ray wavelength. Rough interfaces do not reflect "as well" as flat interfaces; therefore the reflected amplitude from a real interface is less than that predicted by Eq. (6). Generally, this effect becomes more significant with increasing Q , and a measure of interfacial roughness may be thought of as the amount by which the observed reflectivity differs from the reflectivity of a flat interface. This is because of the destructive interference between x-ray waves scattering from each part of the interface due to the path length differences [9]. Accordingly, the XR from a rough interface may be written as [7]

$$V^F \int P(h) e^{iQh} dh = V^F P(Q) \quad (7)$$

where V^F is defined in equation (6), h is a height in the direction normal to the surface and $P(h)$ is a probability distribution function about the average height. The integration is performed over the height-variation of the interface within the x-ray coherence length. The best known form of $P(Q)$ is Debye-Waller type damping [23]. In this limit, $V = V^F e^{-Q^2 \sigma^2 / 2}$ and it is accurate for a large scattering limit and for Gaussian interface fluctuations without lateral correlations. However, more general non-Gaussian damping factors have been considered and found applicable for several types of interfaces [7,24].

An additional caution has to be taken in using Eq. (7) because Q in the equation is not necessarily vacuum momentum transfer. As discussed above, the momentum transfer changes as the index of refraction changes at the interface. Therefore, a rigorous evaluation of Eq. (7) becomes complicated. The simplest approximation, of course, is ignoring the dependence of Q on the index of refraction. Several other possible approximations have been explored in various literatures and it is generally accepted that the geometric mean of momentum transfers for two media, i.e., $Q' = \sqrt{Q_A Q_B}$ [25,26] gives the most satisfactory results. For example, Q' for the vacuum/gold interface is $\sqrt{Q Q_{Au}}$. We also found this

approximation to fit best our data and was used in our data analyses.

For gold sputtered onto silicon under our experimental conditions incident X-rays reflect from *two* interfaces. The reflected intensity that we measure is a result of interference between the reflected amplitude from the vacuum/gold interface and the reflected amplitude from the gold/silicon interface. The interference is due to the path difference between the incident and reflected beams as shown in Fig. 3. Let the reflection amplitudes from the vacuum/gold interface and from the gold/silicon interface be defined as V_1 and V_2 , respectively. In addition, we define the transmission amplitude from vacuum to gold and gold to vacuum as T_{01} and T_{10} , respectively. Then the reflection intensity becomes

$$\begin{aligned} I(Q) &= \left| V_1 + V_2 e^{iQ_{Au}t} T_{01} T_{10} + V_2 e^{iQ_{Au}t} T_{01} T_{10} (-V_1 V_2 e^{iQ_{Au}t}) + V_2 e^{iQ_{Au}t} T_{01} T_{10} (-V_1 V_2 e^{iQ_{Au}t})^2 + \dots \right|^2 \\ &= \left| V_1 + \frac{V_2 e^{iQ_{Au}t} T_{01} T_{10}}{1 - V_1 V_2 e^{iQ_{Au}t}} \right|^2 \end{aligned} \quad (8)$$

where t is the thickness of the film or time of deposition in unit of Å.

Equation (8) includes all the essential features of reflectivity. The next step is the careful evaluation of V 's. X-ray beams emitted from a synchrotron (any x-ray sources for that matter) and subsequently diffracted from monochromator(s) are a collection of many photons whose characteristics (e.g. energies, momenta, and polarizations) have a statistical distribution. Each individual photon is in fact a wave train or a wave packet only within which the interference shown in Eq. (8) occurs. The wave packet is therefore composed of a set of momentum components or has a finite size by the uncertainty principle. Therefore, the V 's should be evaluated by an integration within the finite dimension of the coherency (coherent average). The coherent average is purely due to the intrinsic nature of the source and upstream x-ray optics. A crude estimation of the coherence volume (the size of the wave packet) is approximately $6000 \times 6000 \times 2500 \text{ Å}^3$ for our experimental geometry. In our discussion from now on, we will approximate that the coherence volume is isotropic to 5000 Å in radius. Once the folding is done for a single photon wave packet (coherence volume), it should be statistically (incoherently) averaged again for many photons (incoherent average). If the photons have different directions relative to the sample due to the beam divergence or

if different parts of the sample have different average characteristics such as thickness of the film, the incoherent average becomes necessary to describe the XR correctly. In the case of two interfaces, the inhomogeneity of the thickness and interface width can renormalize the thickness and interface width within the coherent average [7]. However, the misorientation and the beam divergence should be considered for incoherent average. Both misorientation of the surface and the incoming beam divergence can be treated by a spread of θ 's zero or a spread of Q 's zero for small angles. The incoherent average over the Q 's zero can explicitly be performed after the evaluation of $|\dots|^2$ of Eq. (8) as,

$$\langle I(Q) \rangle_{\text{ave}} = \left\langle \left| V_1^F P(\sqrt{Q Q_{Au}}, t) + \frac{V_2^F P(\sqrt{Q_{Au} Q_{Si}}, t) e^{iQ_{Au} t} T_{01} T_{10}}{1 - V_1^F P(\sqrt{Q Q_{Au}}, t) V_2^F P(\sqrt{Q_{Au} Q_{Si}}, t) e^{iQ_{Au} t}} \right|^2 \right\rangle_{\text{ave}} \quad (9)$$

where

$$Q_{Au} = \sqrt{Q^2 - 9.25 \cdot 10^{-5} F_{Au}(Q, \omega)},$$

$$Q_{Si} = \sqrt{Q^2 - 7.81 \cdot 10^{-5} F_{Si}(Q, \omega)},$$

$$V_1^F = \frac{Q - Q_{Au}}{Q + Q_{Au}},$$

$$V_2^F = \frac{Q_{Au} - Q_{Si}}{Q_{Au} + Q_{Si}},$$

$$T_{01} = \frac{2Q}{Q + Q_{Au}},$$

and

$$T_{10} = \frac{2Q_{Au}}{Q + Q_{Au}}.$$

Determining the function $P(Q, t)$ which we will call "momentum space interface profile", in the next section will complete Eq. (8) for our data analyses.

B. Momentum Space Interface Profile

Our discussion of $P(Q, t)$ will be limited to $2 + 1$ dimensions which is relevant to our experiments. The destructive interference between the rays reflecting at different positions on the surface due to the path length difference can be written in terms of a surface integral over the surface area (πD^2) [27].

$$P(Q, t) = \int_{S=\pi D^2} d\vec{x} e^{iQ\{h(\vec{x}, t)-t\}} \quad (10)$$

Since the surface is rough, this integral should be statistically evaluated. For this, we define an equal time *height difference distribution function*, $G(x, t)$ [28], which depends on the distance x between two points on the surface and on time t as,

$$G(x, t) = \langle |h(\vec{x} + \vec{x}_1, t) - h(\vec{x}_1, t)|^2 \rangle_{\vec{x}_1} \quad (11)$$

where it is assumed that the interface is isotropic within the surface dimension d_s . This function has the following meaning. When the surface is divided into small surface elements, the positions of the surface elements can be rearranged into a distribution which is cylindrically symmetric and statistically identical to the original surface. For a given x the surface elements have a Gaussian random distribution about $h(x, t) = t$ with a width $\sqrt{G(x, t)}/2$. In other words, $G(x, t)$ can be rewritten as

$$\begin{aligned} G(x, t) &= 2 \langle [h(\vec{x}, t) - t]^2 \rangle \\ &= 2[\langle h(\vec{x}, t)^2 \rangle - t^2] \end{aligned} \quad (12)$$

Then the surface integral given in Eq. (10) can be rewritten and evaluated using the definition of $G(x, t)$ as,

$$\begin{aligned} P(Q, t) &= \frac{2}{D^2} \int_0^D dx \frac{1}{\sqrt{\pi G(x, t)}} \int_{-\infty}^{\infty} dh' e^{iQh'} e^{-h'^2/G(x, t)} \\ &= \frac{2}{D^2} \int_0^D dx e^{-Q^2 G(x, t)/4} \end{aligned} \quad (13)$$

From the above definition, the width $W(L, t)$ of a finite size surface with a surface area of πL^2 can be obtained from $G(x, t)$ as

$$\begin{aligned}
W^2(L, t) &= \langle \{h(\vec{x}, t) - t\}^2 \rangle_{\pi L^2} \\
&= \frac{1}{L^2} \int_0^L G(x, t) x dx
\end{aligned} \tag{14}$$

Now let us consider the limiting cases of the scaling hypothesis shown in Eq. (1). From the limiting form of the function $f(x)$, we can easily see that $W \sim L^x$ for $t^\beta/L^x \ll 1$ and $W \sim t^\beta$ for $t^\beta/L^x \gg 1$. Using these limiting values we can also find the limiting values for $G(x, t)$. For small L , the right hand side of Eq. (14) becomes $G(L, t)$ and therefore $G(L, t) \sim x^{2x}$. For large L , it becomes $G(\infty, t)/2 + \mathcal{O}\{(1/L)^2\}$ and therefore $G(L, t) \sim t^{2\beta}$. This limiting form comes from the fact that for large L values W saturates to a constant value which depends only on time. To summarize,

$$G(x, t) = \begin{cases} x^{2x}, & \text{for } x^x \ll t^\beta; \\ t^{2\beta}, & \text{for } t^\beta \ll x^x. \end{cases} \tag{15}$$

For clarity, one can rewrite the height-height distribution function in terms of height-height correlation function, $C(x)$ [28],

$$\begin{aligned}
G(x, t) &= 2W^2(\infty, t) [1 - C(x, t)] \\
&= 2\Sigma^2(t) [1 - C(x, t)]
\end{aligned}$$

In Fig. 4, the evolution of an interface (a) and corresponding general behavior of the function $G(x, t)$ (b) are schematically shown for several growth times for illustration.

Here we will make a simple approximation for the function $G(x, t)$ for the evaluation of Eq. (13) because the exact form of $G(x, t)$ is unknown. The approximation shown in Fig. 5 is to divide $G(x, t)$ (thick solid line) into two regions; time-independent part (thin solid curve) where $G(x, t) = Ax^{2x}$ with a proportional constant A and the other x -independent part where $G(x, t) = 2\Sigma^2(\infty, t)$ (thin horizontal line). The two regions join at $x = (\sqrt{2}W/A)^{1/x}$. By substituting this approximation of $G(x, t)$ into Eq. (13), we obtain

$$P\{Q, \Sigma(t)\} = \frac{\{\Sigma(t)\}^{2/x}}{D'^2} \left[\frac{1}{xy^{2/x}} \gamma\left(\frac{1}{x}, y^2\right) \right] + \left\{ 1 - \frac{\{\Sigma(t)\}^{2/x}}{D'^2} \right\} e^{-y^2} \tag{16}$$

where $y = \frac{1}{2}Q\Sigma(t)$ and $D' = (A/\sqrt{2})^{1/x}$. The unknown, time-dependent $\Sigma(t)$, is the key parameter for the scaling behavior of interest. Now Eq. (9) is complete.

The detailed fit procedures to Eq. (9) will be reviewed in the next section. Here we will merely show experimental evidence for Eq. (16), namely justification for the first term in Eq. (16). The first term in Eq. (16) comes from the first region where $G(r, t) \sim x^{2x}$ (thin curve in Fig. 5) and the second term comes from the second region where $G(r, t)$ is constant (thin horizontal line in Fig. 5). The prefactors for each term are the fractional areas within πL^2 . The significance of the first term can easily be shown in XR from thick films. The parameter D' is the x-ray coherence length, ~ 5000 Å in our experiments. Using Eqs. (16,9), we fit one of the last reflectivity scans shown in Fig. 6. The reflectivity and the fits are shown in Fig. 7. The solid line is the fit with Eq. (16) and the dashed line is a fit only with the Gaussian term. As we can see, a significantly better fit can be obtained by using both terms of Eq. (16) rather than the Gaussian term alone. In the inset, three different interface distribution functions are compared for real space and reciprocal space. The solid line is for the case using only the first term of Eq. (16), the dashed line is for the case of the Gaussian term (the second term) only, and the dot-dashed lines are for the case of Lorentzian interface profile discussed in Ref. [7].

C. Dependence of films on argon pressure

To begin this section we will briefly review the sputtering process in our sputtering geometry shown in Fig. 1. In the system there are two pairs of cathodes and grounded anodes which are under a parallel magnetic field created by a pair of permanent magnets (indicated by large X's). By the electric field, E , Ar^+ 's are created, trapped in magnetic field, and accelerated to the cathode. The magnetic field traps the ions within the column of magnetic field. By the bombardment of the Ar^+ 's mostly neutral gold particles are produced and some of them travel to arrive at the substrate located about 5 cm away from the targets. In the sputter-deposition process the argon pressure in the chamber is very important. When the pressure is too high, a few factors limiting the sputter-deposition can occur. First, the ionized argon will suffer too many collisions to reach the target with sufficient kinetic energy

for sputtering. Secondly, the particles sputtered will suffer a great deal of collisions, loose energy and some may return back to the target. Therefore, the sputtering efficiency is low for $P_{Ar} \gg 10$ mTorr. For $P_{Ar} \ll 1$ mTorr, there are not enough Ar^+ for sputtering as explained by Paschen's law [29]. Therefore there is a relatively narrow range of pressure within which sufficient deposition occurs for a given condition.

The mean free path of a sputtered particle $\ell = kT/\sqrt{2}\pi d^2 p$. This gives us a mean free path of ~ 10 cm for 1 mTorr. Within experimental uncertainty of pressure measurements (the pressure at the center of the chamber is expected to be higher than that at the pressure gauge), the high pressure (10 mTorr) was selected so that a particle sputtered from the target collides several times with argon atoms before it reaches the sample surface. The low pressure (1 mTorr) was selected, on the other hand, so that the sputtered particle reaches the sample with few collisions. Therefore, the particles at the high pressure arrive in random directions with significantly reduced kinetic energies. The particles at the low deposition pressure arrive with the initial kinetic energies and without changing the direction of travel.

To our surprise, the reflectivity scans were qualitatively different for the low-pressure and high-pressure depositions. Some scans to illustrate this point are shown in Fig. 8. The high pressure and low pressure data are shown in (a) and in (b), respectively. The gold film thicknesses were 80, 170, 230, 620, and 2420 Å for (a) and 90, 170, 340, 720, and 1000 Å for (b), from top to bottom, respectively.

We will compare the second scans from the top whose thicknesses are nearly identical. They also show the qualitative differences most clearly. In either case, the oscillation periods are quite similar. However, the oscillation amplitude in (a) is large for small Q but rapidly decreases as Q increases. On the other hand, the oscillation amplitude in (b) is small for small Q but decreases slowly as Q increases. A qualitative comparison can be made without detailed analyses of the data. When the film is smooth in all length scales the oscillation amplitude will be large and decrease slowly as Q increases. When the surface is rough in microscopic length scales (comparable to the x-ray wavelength), the oscillation amplitude will decrease rapidly even if the film is extremely smooth in global scales. When the surface

has large length scale fluctuations (comparable to the x-ray coherence length), on the other hand, an incoherent average becomes necessary. In this case, the oscillations for small Q are smeared more than those at large Q (This point can be seen clearly by computer simulation of XR and applying different amounts of incoherent average). From the above qualitative arguments we can conclude that the high pressure samples have surfaces which are microscopically rough but globally smooth, while the low pressure sample is microscopically smooth but globally rough.

Another interesting difference between these two samples can be seen in off-specular scans shown in Fig. 9. These off-specular scans were obtained at the end of each series of measurements. Three scans measured with different perpendicular momentum transfers are shown in (a) for the high pressure film and in (b) for the low pressure film. The perpendicular momentum transfers for these scans are 0.1, 0.125, and 0.15 $\text{\AA}^{-1}$ from the top, respectively. There are significant off-specular scattering in (b) but there are nearly none in (a). The off-specular scattering in (a) indicate that there are structures in size of hundreds of angstroms while there are no structures in such length scales in (b).

To compare the off-specular scans with real space images, STM measurements were performed. In Fig. 10, the STM images are shown; the image for the high pressure sample in (a) and that for the low pressure sample in (b). A simple examination shows that the image for the high pressure sample is rough and the roughness occurs in all length scales. On the other hand, the image for the low pressure sample shows structures whose sizes and distances apart are not completely random. The average distances between these bumps and their sizes are quite consistent with the off-specular scans shown in Fig. 9 (b). The sizes of the bumps and the distances between them are approximately an order of hundred $\text{\AA}$ which is consistent with the off-specular scattering at $\sim 0.01 \text{\AA}^{-1}$.

To check the uniform deposition over the entire sample surface, profilometry was performed. The measurements were performed in air after deposition was completed. Within the sensitivity of the profilometer ($\pm 30 \text{\AA}$) the film thicknesses were uniform over the macroscopic extent (1.3 cm x 1.3 cm) of sample. From the profilometry results, it is clear

that the films grown in our sputtering chamber is homogeneous over the entire sample.

Powder diffraction scans of these samples are shown in Fig. 11. The measurements were made in air using an in-house 12 kW rotating anode x-ray source (CuK_α radiation, $\lambda=1.54$ Å). The data is plotted as intensity (logarithmic scale) versus 2θ . The positions of the Au(111) and Au(200) Bragg reflections are indicated in the figure. These scans, along with rocking curve scans, indicate that both films were textured 2-d powders. The 1 mTorr film consisted of facets with (111) index plane faces oriented parallel to the substrate surface. The 10 mTorr film consisted of a combination of facets having (111) and (200) faces oriented parallel to the substrate surface plane. The characteristic facet size was approximately 50 Å. Powder scans from other sputter deposited gold/silicon samples strongly suggest that a combination of (111) and (200) facets is an effect of P_{Ar} and independent of T over the range 220-350 K.

D. Dependence of films on substrate temperature

Like argon pressure in the chamber, the changes in substrate temperature also affect the film growth. For examples, selected XR scans measured for $P_{\text{Ar}} = 10$ mTorr are shown in Fig. 12. The reflectivity scans are normalized by the calculated reflectivity of a semi-infinite flat gold slab. The normalization emphasizes the effect of the gold/vacuum interface on the measured XR. Each group of XR's shown in Fig. 12 is from a similar deposition thickness and the XR's in each group are for gold deposited at $T = 300, 220, 350$ K when $P_{\text{Ar}} = 10$ mTorr. The film thicknesses for the groups from the top are approximately 80 Å, 170 Å, 230 Å, and 620 Å, respectively. For the substrate temperature of 220 and 300 K, the deposition rates measured from the oscillation frequencies. The deposition times at these two temperatures are quite similar. For the early growth stage (≤ 230 Å) the XR for these two temperatures appear nearly identical. However, by 620 Å the amplitudes of the oscillations of the 300 K sample are obviously smaller than the amplitudes of oscillations of the 220 K sample. The oscillation amplitude is related to interfacial roughness and it was determined that the

300 K film surfaces are rougher than the 220 K film surfaces for the same film thicknesses. Initially this result may seem counter-intuitive. Namely, at lower temperatures one may expect gold to deposit consistent with ballistic aggregation and gold deposited at higher temperatures would have greater mobility resulting in a smoother surface. However, our result is consistent with computer simulation of growth in restricted solid-on-solid model. In this model, growth at lower temperatures leads to a surface composed of large terraces because growth occurs mainly at surface defects such as steps and along kinks. At higher temperatures the surface appears locally rough.

For the substrate temperature of 350 K the deposition rate as determined by changes in the XR oscillation frequencies, is considerably smaller than those measured at lower substrate temperatures. In addition, the oscillation amplitudes are dampened more rapidly (with increasing Q) than those at lower substrate temperatures. The second observation implies that the gold film surface becomes rougher much more rapidly than at lower temperatures. This is evident from the XR scans shown in Fig. 12. Since the sputtering rate from the target and number of impinging gold atoms should be independent of the substrate temperature, the apparent slow deposition rate can be explained by clustering of gold due to sufficient mobility of gold atoms at 350 K. In wetting terminology, the film is in an incomplete wetting situation, therefore, the film and bulk gold coexist. Since the coexisting bulk occupies only small surface area, the linear relation between the average film thickness and oscillation frequency in XR scans is no longer valid. Since many of the incoming particles go into the bulk gold phase, the film phase of the sample grows at a slower rate.

E. Scaling behaviors

The specular XR data measured during the deposition of gold on silicon are shown in Fig. 6. A series of reflectivity scans are plotted with respect to perpendicular momentum transfer and deposition time. The relevant deposition parameters were substrate temperature (T) and Ar gas sputtering pressure (P_{Ar}). These parameters for the sets of data from

the top were $T = 220, 300$, and 350 K at $P_{Ar} = 10$ mTorr and $T = 230$ and 300 K at $P_{Ar} = 1$ mTorr, respectively. The background was determined by performing XR scans in an off-specular condition, i.e. $\theta = \frac{2\theta}{2} \pm 0.2$ degrees (at the specular condition $\theta = \frac{2\theta}{2}$). This background scan was made only at the end of each series of scans. The determined background was then subtracted from the data for data analysis. Since the background increases as the film thickness increases, the measured background at the end of a series is an over-estimation for most of the previous scans. However, the background is nearly negligible for most early scans and should become closer to the estimated background as the deposition progresses. We find that the background subtraction becomes significant only for the last few scans. Therefore, the estimation of background only from the last scan is fairly good approximation to measuring the background point by point and scan by scan. In short, our way of background subtraction do not affect the fitting of data nor conclusions drawn from the fit parameters in following discussions. The measurements were done in a spill-over geometry, the incident x-ray beam intercepted by the sample increases as the scattering angle increases until the foot print of the x-ray beam on the sample becomes larger than the size of the samples. This geometric effect has been corrected by integrating the incident x-rays from the beam profile.

As discussed in Sec. IV A, the oscillations in the XR arise from interference effects between the silicon/gold and gold/vacuum interfaces. The oscillation period is inversely proportional to the thickness of medium 1 in Fig. 3, in our case, the gold. As shown in Fig. 6, the oscillation period decreases as the deposition increases. The oscillation amplitude is then proportional to the Fourier transformation of gold/vacuum interface. As the gold thickness increased beyond approximately $1300 \text{ \AA}$ the oscillations were no longer resolvable due to a combination of instrumental resolution, absorption of x-rays through gold, and the relatively large roughness of the gold/vacuum interface. When the thickness of gold and the roughness of gold/vacuum interface become so large that the absorption of x-ray through gold becomes severe, the interference disappears. In this case the reflection from the gold/vacuum interface is strong for small Q values but rapidly decreases because of its roughness. The

reflection from the gold/silicon interface is very weak for small Q values (small angles; long path length through gold) due to the absorption through gold but becomes significant at large Q (large angles; short path length through gold) values compared to that from the gold/vacuum interface, because the gold/silicon interface is sharp and remains unchanged throughout the deposition. Therefore, XR at low Q values is mainly from the gold/vacuum interface and XR at high Q values is mainly from the gold/silicon interface. In the region where the oscillations are discernible, the gold film thickness can be accurately determined from the oscillation period. For a thick film the thickness is determined from the absorption of the scattering from the gold/silicon interface through gold layer. This also provides a fairly accurate thickness.

One of the key factors in determining accurately the width of the gold/vacuum interface is the cleanliness of the silicon surface. Even a small amount of fractional surface contamination can lead to changes in the gold density at the interface and it can strongly modulate or affect the reflectivity. To ensure that the silicon surface was free of contamination, the surface was baked before the deposition of gold. Figure 2 shows the XR of a typical silicon surface measured in vacuum (10^{-5} Torr) at $T = 300$ K before gold deposition. The XR was recorded before (open circles) and after (filled circles) baking the silicon at 500 K. Background was subtracted from the measured XR and the aforementioned geometric correction was also applied. The solid lines represent the best fits to the XR. An equation similar to Eq. (9) was used in the modeling of all the XR presented here. The modulation in reflectivity scan (open circles) indicates that there should be an extra interface besides the silicon surface, likely due to the presence of a hydrocarbon-like layer adsorbed onto the silicon surface. The best fit was obtained by using a simple Gaussian distribution to describe the interfacial roughness. The best fit parameters were: the silicon surface roughness was $3.1 \text{ \AA}$, the adsorbed layer thickness (l) was $19.4 \text{ \AA}$, and the adsorbed layer electron density was $0.55 \text{ e}^-/\text{\AA}^3$. This electron density is roughly equivalent to that of water. The fraction of the second interface for the XR data recorded after bake-out to 500 K was fit to zero indicating that a single interface (silicon/vacuum) model is sufficient and contamination of the surface is negligible.

The fits of Eq. (9) to the data shown in Fig. 6 are done in three steps. First, several parameters including density of gold, x-ray coherence length, instrumental resolution and roughness of the gold/silicon interface, which is expected not to change during deposition, were allowed to vary during fitting in addition to the film thickness and the parameter Σ in Eq. (9). By doing so, we can test whether any of those fit parameters change significantly from scan to scan. In addition, some of those parameters which can be estimated from our experimental geometry, could be tested with whether the parameters are consistent with the estimations. We found that the density of gold is 1.00 or close to 1.00 for the entire deposition range. The fit value of x-ray coherence length, D' , turns out to be $5.5(5) \times 10^3 \text{ \AA}$ while the estimation from our experimental resolution is an anisotropic one which is approximately 2500 $\text{\AA}$ in the transverse direction and 6800 $\text{\AA}$ along the longitudinal direction on the sample surface along the incident x-ray beam. The roughness of the gold/silicon interface was 3.0(5) $\text{\AA}$ and remains unchanged over the entire fit range. In the next step, all the fit parameters are fixed to the optimum values for the entire scans in a series and only the film thickness, $\bar{h}$, and the parameter, Σ , are allowed to vary during the fitting. The fit values for $\bar{h}$ and Σ were similar to the previous fit values (as expected) with improved statistics. The fit values of $\bar{h}$ for a series of scan (220 K and 10 mTorr) vs. deposition time is shown in Fig. 13 for an example. As we can see the linearity of the $\bar{h}$ is very good and the deposition rate was determined from it. Finally, putting the deposition rate into the fitting, the parameter Σ , which is of our prime interest in the point view of scaling, was determined. A slight improvement of the statistics was found.

Let us go back to Eq. (16). $P(Q, t)$ consists of two terms. The first term is for the part of surface with power-law height-height correlations and the second term is for the part of surface with Gaussian correlations. In this expression, the exponent χ is unknown and needed to be determined. In our study χ was determined by two methods; by fitting the XR data and by calculating from STM images.

The exponent χ was not a fit parameter because of the complexity of the analytic form of the incomplete gamma function in our fitting program. Therefore several values of χ

predicted in the literature were tried until a reasonable fit of Eq. (9) was determined. The most reasonable value of χ was 2/5. Figure 7 shows an XR scan of gold/silicon (open circles) measured at $P_{Ar} = 10$ mTorr and $T = 220$ K. The solid line is the fit using Eqs. (9,16). One can wonder if the first term in Eq. (16) is really necessary to fit the data. To check this we fit the data with second term only, i.e., assuming a Gaussian interface profile. The dashed line is the best fit with this assumption. We can see that the dashed line clearly misses the data point near $0.13 \text{ \AA}^{-1}$. To understand the fit behavior better, two insets are shown in the same figure. The lower inset shows a set of lines; the solid line is the incomplete gamma function shown in Eq. (16), the dashed line is for Gaussian function, and the dot-dashed line is Lorentzian functional form shown for comparison. In the upper inset, their corresponding real space interface profiles are shown for illustration.

The second method of determining χ is from STM images. Since the STM images shown in Fig. 10 are made of digitized numbers one can directly compute the height-difference distribution function, $\sqrt{G(x,t)}$, from Eq. (11). The calculated $\sqrt{G(x,t)}$ from Fig. 10(a) at $t = 3500 \text{ \AA}$ is shown in Fig. 14 as a solid line. Note that the solid line is remarkably similar to functional form shown in Fig. 3(b). It increases initially with a smooth, power-law behavior but eventually saturates to a steady state value. The dashed line is a power-law fit to $\sqrt{G(x,t)} \sim r^\chi$ for $r < 2000 \text{ \AA}$ and the fit value of χ was 0.40(2), consistent with the value also found from fitting the XR scans. In the inset the real-space interface profile (open circles) calculated from the same STM image is shown for illustration. The solid line is a Fourier transformation of Eq. (16) calculated with the best fit parameters.

In figure 15 $\Sigma(t)$ of gold deposited on silicon at $P_{Ar} = 10$ mTorr and $T = 220$ K (open circles) and 300 K (filled circles) is plotted as a function of deposition time. The solid lines represent the best power law fits to the data. The exponent β was 0.42(2) for the 220 K data and 0.40(2) for the 300 K data. The expected behavior $\beta = 1/2$ (random deposition) and $\beta = 1/4$ (RSOS model [15]) are also shown for comparison. As we can see the values of exponent β are smaller than and do not agree well with the predicted values of various models. In the case of low pressure data shown in Fig. 16, the situation is very different.

First, the fit value of Σ is smaller than that for a film with the similar thickness grown at the higher pressure. For initial deposition there is no increase of the interfacial width until it reaches approximately 400 Å. Since the film was predeposited for 50 to 60 Å at 10 mTorr the roughness of the film does not increase by deposition at the low pressure by filling valleys. However the value of Σ^2 increases eventually and the solid line is a fit. The widths for the low pressure data were fit to $\sqrt{\Sigma_0^2 + at^{2\beta}}$ and the value of $\beta = 0.5$ was found.

V. CONCLUSIONS

The effect of sputter deposition conditions on the scaling behavior is discussed. Also, the interface topography, in the both the directions normal and lateral to the substrate plane, is sensitive to the momenta of depositing gold particles. The results presented here indicate that gold films formed by deposition of thermalized gold particles (small incident momenta) are locally rough but globally smooth, while gold films formed by deposition of gold particles with large incident momenta (traveling in straight-line trajectories) are locally smooth but globally rough. Incoherent averaging was not needed to model the 10 mTorr data, but was required to model the 1 mTorr data. We also introduce a simple expression to describe x-ray reflectivity from rough interfaces. The model makes use of the dynamic scaling functional form, Eq. (1) to model interfacial roughness. This model is compared to a simple Gaussian distribution typically used to describe interface roughness. We found that the interfacial width does exhibit scaling behavior for the films grown under high argon pressure. The exponents found in our study for high pressure data were $\chi = 0.40$ and $\beta = 0.40(2)$. One of the key features for the dynamic scaling behavior is the fact that the value χ does not change over time. Because of it, the off-specular reflectivity scans measured during growth should show an identical functional shape for large $Q_{\parallel}$. A series of off-specular reflectivity scans do indeed show the expected behavior [30]. The dynamic scaling behavior was not evident for the low pressure films.

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FIGURES

FIG. 1. The sputtering chamber and its faced-magnetron sputter guns used in this study is schematically shown. The incident and scattered x-ray beams are approximately perpendicular to this page. The radial electric (E) and axial magnetic (H) fields are indicated. The drawing was adapted from Fig. 1 of Zheng, et al. [18]

FIG. 2. The x-ray reflectivity of a typical silicon substrate is plotted before (open circles) and after (filled circles) heating to 500 K in vacuum. The solid lines are the best fits to the data as described in the text.

FIG. 3. Specular x-ray reflectivity from two interfaces. The optical path difference between the two rays scattered from the two interfaces is indicated by the dashed segments.

FIG. 4. (a) A schematic drawing of a growing interface. The thin lines schematically show the history of the interface during growth. (b) The corresponding evolution of height-height distribution functions is schematically shown.

FIG. 5. The approximation for the height-height distribution function used in our study. A smooth functional form is approximated to the two regions with simple analytic forms.

FIG. 6. Specular x-ray reflectivity (logarithmic scale) is plotted against perpendicular momentum transfer (Q), and deposition time (logarithmic scale). The unit of the time axis is in $\text{\AA}$ (1 $\text{\AA}$ deposition per approximately 2 seconds). The deposition conditions from the top were $P_{\text{Ar}} = 10$ mTorr and $T = 300$ K, $P_{\text{Ar}} = 10$ mTorr and $T = 220$ K, $P_{\text{Ar}} = 10$ mTorr and $T = 350$ K, $P_{\text{Ar}} = 1$ mTorr and $T = 300$ K, $P_{\text{Ar}} = 1$ mTorr and $T = 300$ K, $P_{\text{Ar}} = 1$ mTorr and $T = 220$ K, respectively.

FIG. 7. Specular x-ray reflectivity (circles) of the 3500 Å thick film grown at $T=220$ K and $P_{Ar}=10$ mTorr. The solid line is the fit based on Eq. (16) and the dashed line is based on a Gaussian interface profile. See the text for discussion.

FIG. 8. Examples of the best fits (solid lines) to the x-ray reflectivity data (filled circles) using Eq. (9) of the text. The deposition conditions were $T=220$ K and $P_{Ar}=10$ mTorr for (a) and $T=300$ K and $P_{Ar}=1$ mTorr for (b). The gold film thicknesses were approximately 80, 170, 230, 620, and 2400 Å from top to bottom, respectively.

FIG. 9. Transverse $(0.1\ K\ 0)$, $(0.125\ K\ 0)$, and $(0.15\ K\ 0)$ scans from the top, respectively for gold sputter deposited onto silicon at $T=300\ K$ and $P_{Ar}=1\ mTorr$ (a) and at $T=220\ K$ and $P_{Ar}=10\ mTorr$ (b). The scans were recorded in air after the gold deposition was completed. The gold thicknesses were $3500\ \text{\AA}$ for (a) and $3800\ \text{\AA}$ for (b). The solid lines are guides to the eye.

FIG. 10. The STM images of the same samples from which the XR scans shown in Figs. 9,8.

FIG. 11. Powder diffraction scans from gold sputter deposited onto silicon at (a) $T=300$ K and $P_{Ar}=1$ mTorr and (b) $T=220$ K and $P_{Ar}=10$ mTorr. The scans were recorded in air after the gold deposition was completed. The gold thickness was approximately $3500 \text{ \AA}$ in both cases. They are plotted on a logarithmic scale and one of them is offset for clarity. The expected peak positions for the Au(111) and Au(200) Bragg reflections are indicated by the arrows.

FIG. 12. Selected sets of the high pressure data are shown to illustrate the temperature dependences. The temperatures in each set are 220, 300, 350 K. The thicknesses for the sets from the top are 85 Å, 170 Å, 350 Å, and 800 Å, respectively.

FIG. 13. The thickness vs. deposition time. The linear dependence of the thickness is evident.

FIG. 14. The height-height distribution function calculated from the STM image of the high pressure sample shown in Fig. 10(a). The interface distribution function is also calculated from the image and shown in the inset.

FIG. 15. The width of the gold-vacuum interface is plotted vs. gold thickness (log-log scale) under the following deposition conditions: $T=350$ K and $P_{Ar}=10$ mTorr Ar (filled circles) and $T=300$ K $P_{Ar}=10$ (open circles). The solid lines are the best power law fits to the data ($\beta=0.4$). The dashed line ($\beta=0.25$) and dot-dashed line ($\beta=0.5$) are provided for reference.

FIG. 16. The width of the gold-vacuum interface for gold deposited at $T=220$ K and $P_{Ar} = 1$ mTorr is plotted against deposition time in a linear scale. The solid line is a fit with $\beta = 0.5$.