Surface morphological evolution of epitaxial CrN(001) layers

J. R. Frederick and D. Gall

Department of Materials Science and Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180

(Received 13 June 2005; accepted 22 July 2005; published online 9 September 2005)

CrN layers, 57 and 230 nm thick, were grown on MgO(001) at $T_s=600$–800 °C by ultrahigh-vacuum magnetron sputter deposition in pure N$_2$ discharges from an oblique deposition angle $\alpha=80^\circ$. Layers grown at 600 °C nucleate as single crystals with a cube-on-cube epitaxial relationship with the substrate. However, rough surfaces with cauliflower-type morphologies cause the nucleation of misoriented CrN grains that develop into cone-shaped grains that protrude out of the epitaxial matrix to form triangular faceted surface mounds. The surface morphology of epitaxial CrN(001) grown at 700 °C is characterized by dendritic ridge patterns extending along the orthogonal (110) directions superposed by square-shaped super mounds with (100) edges. The ridge patterns are attributed to a Bales-Zangwill instability while the supermounds form due to atomic shadowing which leads to the formation of epitaxial inverted pyramids that are separated from the surrounding layer by tilted nanovoids. Growth at 800 °C yields complete single crystals with smooth surfaces. The root-mean-square surface roughness for 230-nm-thick layers decreases from 18.8 to 9.3 to 1.1 nm as $T_s$ is raised from 600 to 700 to 800 °C. This steep decrease is due to a transition in the roughening mechanism from atomic shadowing to kinetic roughening. Atomic shadowing is dominant at 600 and 700 °C, where misoriented grains and supermounds, respectively, capture a larger fraction of the oblique deposition flux in comparison to the surrounding epitaxial matrix, resulting in a high roughening rate that is described by a power law with an exponent $\beta>0.5$. In contrast, kinetic roughening controls the surface morphology for $T_s=800$ °C, as well as the epitaxial fraction of the layers grown at 600 and 700 °C, yielding relatively smooth surfaces and $\beta<0.27$. © 2005 American Institute of Physics. [DOI: 10.1063/1.2035307]

I. INTRODUCTION

Transition-metal (TM) nitrides are well known for their remarkable physical properties including high hardness and mechanical strength, chemical inertness, and high-temperature stability. As a result, they are widely studied and have become technologically important for applications such as hard wear-resistant coatings, diffusion barriers, and optical coatings. CrN has gained considerable interest over the past several years due to its superior high-temperature oxidation resistance, considerably higher than that of TiN, the primary industrial TM-nitride hard coating. CrN has also been shown to possess high wear and corrosion resistance, to provide improved system adherence as an interfacial layer between diamond films and steel, and to offer potential for use in phase-shift masks for photolithography and etch-resistant hardmasks for x-ray absorber patterning.

We have previously reported on the growth of epitaxial CrN layers and have determined the fundamental physical properties including mechanical, electronic transport, and optical properties and their relation to the CrN band structure. These epitaxial CrN layers exhibit unique 1-mm-wide nanopipes which are open pores that extend through the entire layer thickness. Such nanopipes are particularly promising for future use as channels in single-molecule chemistry, lab-on-a-chip applications, molecular sieving, and DNA sequencing. The nanopipe formation mechanism is unknown but is presumably related to a complex interplay of anisotropic surface diffusion processes and atomic shadowing from a periodic surface mound structure. The present study provides the fundamental insight into the effect of atomic shadowing on the surface morphological evolution of epitaxial CrN(001) layers, which is required to develop an atomistic understanding of the nanopipe formation process.

In this article, we present the results on an investigation of the surface morphology of CrN layers grown on MgO(001) as a function of deposition temperature $T_s$ between 600 and 800 °C and layer thickness $t=75–230$ nm by ultrahigh vacuum (UHV) sputter deposition. Deposition was done at an oblique angle of 80° in order to enhance the atomic shadowing and directly probe its effect on the surface morphological evolution. Growth at 600 °C leads to layers that consist of an epitaxial matrix which contains misoriented cone-shaped grains that lead to triangular faceted surface mounds. The CrN layers grown at 700 and 800 °C are complete single crystals with surfaces that exhibit dendritic mounds with fingers extending along the orthogonal (110) directions. In addition, square-shaped supermounds which protrude out of the underlying matrix develop in layers grown at 700 °C. Quantitative roughening analyses indicate that two distinct roughening processes are responsible for the final surface morphology: kinetic roughening yields regular surface mound structures which increase in size as the layer thickness increases, following a power law with a roughening exponent $\beta<0.27$. In contrast, roughening due to atomic

Electronic mail: gall@rpi.edu
shadowing yields a much higher roughening rate with \( \beta > 0.5 \) and causes surface protrusions, that is, misoriented grains at 600 °C and supermounds at 700 °C.

II. EXPERIMENTAL PROCEDURE

All CrN\(_x\) layers were grown in a load-locked multichamber UHV stainless-steel dc magnetron sputter deposition system. The pressure in the sample introduction chamber was reduced to less than 1.3 × 10\(^{-5}\) Pa (1 × 10\(^{-7}\) Torr), using a 60 l s\(^{-1}\) turbomolecular pump (TMP), prior to initiating substrate exchange into the deposition chamber which has a base pressure of 1.3 × 10\(^{-7}\) Pa (1 × 10\(^{-9}\) Torr), achieved using a 520-l s\(^{-1}\) TMP. A water-cooled 7.5-cm-diameter Cr target with a purity of 99.95% was positioned at 10 cm from the substrate with the target center within the plane of the substrate surface. This arrangement yields a deposition flux which impinges at the substrate with an average azimuthal angle of 80°, measured with respect to the sample normal. The angular distribution of the deposition flux, due to the finite size of the sputter source and determined using the erosion track on the target, ranges from 77°–90°, excluding the effects from vapor-phase scattering.

The substrates were polished 10 × 10 × 0.5-mm\(^3\) MgO(001) wafers cleaned with successive rinses in ultrasonic baths of trichloroethylene, acetone, methanol, and deionized water and blown dry with dry N\(_2\). The wafers were then mounted on a molybdenum holder and inserted into the sample introduction chamber for transport to the growth chamber where they were thermally degassed at 800 °C for 1 h, a procedure shown to result in sharp MgO(001) 1 × 1 reflection high-energy electron-diffraction patterns.\(^{14}\) 99.99%-pure N\(_2\) was further purified using a Micro Torr purifier and introduced through metering valves to reach a constant chamber pressure of 2.6 Pa (20 mTorr), which was measured using a capacitance manometer. Just prior to initiating deposition, the targets were sputter cleaned for 5 min while the substrate was covered with a protective disk. Sputtering was carried out at a constant power of 150 W, yielding a deposition rate of 3.8 nm/min. The film growth temperature, 600 ≤ \( T_s \) ≤ 800 °C including the contribution due to plasma heating, was measured with a pyrometer that was cross calibrated by a thermocouple within the sample stage. The substrate was continuously rotated about the polar axis with 50 rpm, resulting in an overall circularly symmetric deposition flux. Following deposition, the samples were allowed to cool to <50 °C before transferring them to the load-locked chamber which was then vented with dry N\(_2\).

Film surface morphology was investigated by tapping-mode atomic force microscopy (TMAFM) using a Digital Instruments Multimode SPM Nanoscope III with Nanodevices Tap300 silicon tips with tip radii of 10 nm. Linear-planarized height profile images were obtained by removing sample tilt effects with standard software. The root-mean-square (rms)-surface roughness \( \sigma \) and average mound heights were then determined from the entire images as well as from the selected areas that exclude misoriented grains and supermounds, as described in the Results section.

Layer microstructures were analyzed by cross-sectional transmission electron microscopy (XTEM) using a Philips CM12 microscope with a LaB\(_6\) filament operated at 120 kV. Cross-sectional specimens were prepared by first gluing two samples film to film with M-bond 610 and then cutting vertical sections with a wire saw. These sections were mechanically thinned with SiC to a specimen thickness of 30 µm. Final thinning to electron transparency was achieved by ion milling using a 5.0-kV Ar\(^+\)-ion beam incident at 12 °.

III. RESULTS AND DISCUSSION

Figure 1(a) shows an atomic force microscopy (AFM) image of a 57-nm-thick CrN layer grown at 600 ° C. The most dominant features in the surface morphology are the surface protrusions that appear as bright speckles in the micrograph. They have a density of 44 µm\(^{-2}\) and their width, as determined by linear surface height profile analyses on 20 protrusions, ranges from 41 to 123 nm, with an average width of 73 nm. The corresponding height range is 24 to 63 nm, with an average protrusion height of 40 nm. The surface between the protrusions exhibits a mound structure with a rms-surface roughness of 2.3 nm. This value is considerably smaller than 8.6 nm, the rms-surface roughness of the entire surface, that is, including the surface protrusions. Figure 1(b) is an AFM micrograph from a 230-nm-thick layer grown under identical conditions as the one shown in Fig. 1(a), but with a four times longer deposition time, that is, a four times larger layer thickness. The surface morphology is still dominated by surface protrusions, however, their density decreased by more than an order of magnitude, from 44 µm\(^{-2}\) for \( t = 57 \) nm to 3 µm\(^{-2}\) for \( t = 230 \) nm. They exhibit a triangular lateral shape, which is consistent with the XTEM analyses described below, showing that the protrusions are due to misoriented grains. The width and height of the protrusions range from 249 to 359 nm and from 110 to 183 nm.
respectively, with average width and height values of 281 and 138 nm, respectively. Comparing these values to those for the 57-nm-thick layer shows that the average width and height of surface protrusions increases by factors of 3.8 and 3.5, respectively, and the height-to-width aspect ratio remains nearly constant at ~0.5, when the layer thickness is increased by a factor of 4. The surface between the protrusions, which constitutes ~85% of the overall surface, exhibits a mound structure with an rms-surface roughness of 3.0 nm. This part of the surface resembles a cauliflower-type morphology which is common for deposition conditions where surface diffusion is negligible, that is, conditions where the incoming deposition flux is characterized by “hit and stick.” However, the characteristic length scale of the surface mounds in the growth direction is approximately one order of magnitude smaller than that within the surface plane. Therefore, the resemblance of this surface to a cauliflower is somewhat artificial and caused by the exaggerated z scale in the AFM image. The dark areas around the triangular surface protrusions in Fig. 1(b) indicate the surface depressions caused by a reduced growth rate due to atomic shadowing from the elevated protrusions.

We attribute the decrease in number density and the increase in size of the surface protrusions to a competitive growth mode. During growth, surface protrusions capture a larger fraction of the incoming deposition flux than the surrounding matrix, due to atomic shadowing effects that are particularly strong because of the purposely chosen oblique deposition angle of 80 °. Consequently, their growth rate is exacerbated leading to a strong growth both in plane as well as along the layer growth direction. However, if two or multiple protrusions are close together, as is the case for the surface shown in Fig. 1(a), the atomic shadowing will favor the growth of one of these protrusions while the growth of the others is suppressed. This leads to a competitive growth mode where the larger protrusions grow at the expense of the smaller ones which die out.

Figure 2(a) is a typical [100]-zone-axis XTEM image from a 500-nm-thick CrN/MgO(001) layer grown at 600 °C. The most prominent features in the XTEM micrograph are the two cone-shaped grains that stick out of the surface. The corresponding selected-area electron-diffraction (SAED) pattern in Fig. 2(b) shows that these grains are misoriented grains with the same cubic rocksalt crystal structure as the surrounding layer which is a single-crystal CrN(001). The misoriented grains, also shown in larger magnification in Fig. 3(c), appear brighter than the surrounding matrix since their misorientation causes less electron scattering along the imaging direction which is aligned with the [100] direction of the MgO(001) substrate and CrN(001) layer. The micrograph shows an abrupt interface between the MgO(001) substrate and the CrN layer. The apparent decrease in layer thickness from the left to the right in the micrograph is due to the thinning process by ion milling, which caused the top portion of the CrN layer on the right side to be milled away. There is some adhesive (used for XTEM sample preparation) observable on the layer on the left side of the image, indicating that the layer appears in the full size on this side, where it has a measured thickness of 475 nm, close to its nominal thickness of 500 nm, and a surface roughness with a peak-to-valley height of ~8 nm. The 100 selected-area diffraction pattern in Fig. 2(b), obtained with a 400-nm aperture centered in the middle between the two misoriented grains, exhibits symmetric single-crystal reflections, some of which are indexed in Fig. 2. These reflections do not change when the aperture is moved towards the substrate, indicating that the layer is a single crystal with a cube-on-cube epitaxial relationship with the substrate: (001)_{CrN}∥(001)_{MgO} with [100]_{CrN}∥[100]_{MgO}. In addition, the SAED shows the weak diffraction spots, as for example, those indexed as 111 and 222 in Fig. 2. They are identified to arise from cubic CrN and only appear if the aperture includes one or multiple cone-shaped grains, showing that these grains are misoriented CrN.

The XTEM analysis in Fig. 2 shows that the CrN layer deposited at 600 °C initially grows epitaxially until secondary nucleation leads to the formation of incommensurate misoriented CrN grains. The nucleation of these grains can be attributed to a combination of surface irregularities, such as cusps caused by high roughness, and local surface regions stochastically encountering an insufficient N supply to sustain epitaxial growth, as previously reported for TaN. The misoriented grains grow then in competition with the epitaxial layer and form a cone shape. The (001) surface of CrN is expected to have the lowest surface energy, based on similarities to TiN. Thus, the misoriented grains, once nucleated, expose higher-energy surfaces to the growing flux and experience enhanced growth rates, as reported previously for TiN, Ti1-xAlxN, ScN, and δ-TaN growth and in Monte Carlo simulations of fcc film deposition. In each of these cases, the effect can be explained as being due to anisotropies in surface diffusivities and adatom potential energies. That is, the average adatom residence time is significantly higher at lattice sites on low diffusivity (low potential energy) versus high diffusivity (high potential energy) surfaces. Diffusing adatoms that sample sites on both sides of the grain boundary between the epitaxial matrix and the

![Figure 2](image-url)
misoriented grains have a higher probability of finally being incorporated at the low-diffusivity surface of misoriented grains, which provides the more stable, lower potential-energy sites.

Once a misoriented grain protrudes above the epitaxial CrN(001) layer, as shown in Fig. 2(c), its growth rate is further enhanced due to atomic shadowing resulting from the large average azimuthal deposition angle of 80°. The protruding grains collect a larger fraction of the incident deposition flux compared to the 001-oriented epitaxial region of the film. Thus, the misoriented grains grow faster than the surrounding matrix yielding surface protrusions, as observed in the AFM micrographs in Fig. 1. This growth mode also results in lateral growth which yields an increase in grain width as a function of layer thickness, as observed both in our AFM and XTEM analyses.

Figure 3 shows typical AFM images from CrN layers grown at 700 °C with thicknesses of 57 and 230 nm in (a) and (b), respectively. The surface morphologies are characterized by dendritic ridge patterns extending along the orthogonal (110) directions superposed by square growth mounds with edges aligned along the (100) directions, which are the low-energy Cr–N bond directions.10 The square-shaped mounds are considerably (up to 5 times) taller than the ridges, and are in the following referred to as “super-mounds.” Their widths are 70 to 85 nm for the 57-nm-thick layer, and 275 to 383 nm for the 230-nm layer. The average lateral mound size increases from 72 to 332 nm, the average mound height increases from 3 to 26 nm, and the density decreases from 48 to 1.3 m−2, as the layer thickness increases by a factor of 4 from 57 to 230 nm. We attribute the growth of supermounds as a function of layer thickness to the preferential growth that occurs for features that protrude out of the surface due to atomic shadowing, comparable to the process that causes exacerbated growth of misoriented grains at 600 °C, discussed above.

The formation of ridges and secondary dendritic finger structures along the orthogonal (110) directions can be attributed to a Bales-Zangwill instability.26 That is, growth of CrN(001) layers at ≥700 °C proceeds under relatively high adatom mobility conditions, for which adatom incorporation occurs primarily at step edges (rather than via island nucleation). This, in turn, results in denuded zones near ascending step edges with corresponding adatom concentration gradients extending out into the adjacent terraces. The surface steps themselves, which are rough on large length scales, are composed locally of low-energy 100 and 010 facets giving rise to alternating outward-facing convex corners and inward concave corners. The convex regions, due to the adatom concentration gradient, grow faster than the concave regions giving rise to the formation of dendritic or fingerlike structures along the orthogonal (110), directions. Large scale AFM scans (not shown) reveal that the layers grown at 700 °C contain also some misoriented grains, however, with a 6 and 4 times smaller number density, for t=57 and 230 nm, respectively, than what is observed in layers grown at 600 °C. The highly reduced number density of misoriented grains at elevated temperatures is likely due to the suppression of their nucleation, which is, as described above, strongly affected by the surface morphology. Elevated temperatures lead to higher adatom mobilities, smoother surfaces, and a reduced nucleation probability for misoriented grains.

Figure 4(a) is a typical [100]-zone-axis cross-sectional transmission electron micrograph from a 57-nm-thick CrN(001) layer deposited at 700 °C. The corresponding SAED pattern in Fig. 4(b), obtained with a 400-nm aperture centered at the substrate/layer interface, consists of overlapping symmetric 002 and 022 reflections, signifying a cube-on-cube epitaxial relationship: (001)_{CrN}//(001)_{MgO} with [100]_{CrN}//[100]_{MgO}. The spots that emanate from the layer and the substrate overlap nearly perfectly since the difference between the room-temperature lattice constants for the CrN layer and the MgO substrate, 0.4162 and 0.4213 nm, respectively, is only 1.2%.10 The most prominent features in Fig.

![Figure 3](https://example.com/figure3.png)

**FIG. 3.** Atomic force micrographs from CrN/MgO(001) layers deposited at 700 °C from an oblique angle α=80° with thicknesses of (a) 57 nm and (b) 230 nm.

![Figure 4](https://example.com/figure4.png)

**FIG. 4.** (a) Cross-sectional transmission electron micrograph near the [100]-zone axis with (b) a corresponding selected-area electron-diffraction pattern and (c) a higher magnification micrograph showing an inverted pyramid, from a 57-nm-thick CrN/MgO(001) layer grown at 700 °C with an oblique deposition angle α=80°.
The gaps are terminated by tilted smooth surfaces on the substrate surface normal and exhibit a shadowing condition, as reported in Ref. 29. The simultaneous vertical and horizontal growth under anisotropic deposition conditions, as shown in Figs. 3 and 5, likely results from atomic shadowing, comparable to the previously reported nanopipes in transition-metal nitrides,10,16,22,27,28 However, in the present study, these voids are tilted by an angle of 32° with respect to the substrate surface normal and exhibit a width that increases with layer thickness, from 1 to 3 nm. The gaps are terminated by tilted smooth surfaces on the lower (continuous layer) side, but form a nanostaircase structure with {100} facets on the upper (pyramid) side. The step size of this nanostaircase is ~3 nm. We attribute the formation of nanostaircases to kinetic faceting, caused by a simultaneous vertical and horizontal growth under anisotropic shadowing conditions, as reported in Ref. 29.

Figures 5(a) and 5(b) are the AFM micrographs from 57- and 230-nm-thick CrN(001) layers grown at 800 °C, respectively. The surfaces exhibit, in contrast to those from layers grown at 600 and 700 °C, no misoriented grains or supermounds. The morphology of the 57-nm-thick layer (Fig. 5(a)) is characterized by 100–200-nm-wide irregularly shaped surface mounds with some edges along the ⟨100⟩, directions and dendritic fingers along ⟨110⟩. We attribute the complex mound shape to unidirectional coalescence of approximately square-shaped mounds with edges along the low-energy ⟨100⟩, directions that form during the initial stages of layer growth. This coalescence is then followed by preferential growth along the ⟨110⟩, directions, due to a Bales-Zangwill instability described above. The elongation along ⟨110⟩, becomes much more pronounced with increasing layer thickness as indicated by the surface of the 4 times thicker layer shown in Fig. 5(b), which is dominated by up to 700-nm-long ridges along orthogonal ⟨110⟩, directions. The ridges form due to kinetic roughening which is caused by the presence of an Ehrlich-Schwöbel barrier for adatom migration over descending step edges.30 The Bales-Zangwill instability causes a higher capture rate of convex step-edge corners and a preferential in-plane growth along ⟨110⟩, directions. Similar ridge patterns have previously been observed on surfaces of epitaxial understoichiometric TiN layers and have been attributed to a relatively high adatom mobility.31 Correspondingly, the increasing dominance of the ⟨110⟩ oriented surface mounds, when comparing the surface morphologies in Figs. 3(b) and 5(b) from layers grown at 700 and 800 °C, respectively, is attributed to the increasing adatom mobility at increasing growth temperature.

The cross-sectional transmission electron micrograph of a CrN(001) layer grown at 800 °C is shown in Fig. 6. The micrograph, taken near the [100]-zone axis from a 57-nm-thick CrN/MgO(001) layer grown at 800 °C with an oblique deposition angle α=80°.
with the directly observed increase in both lateral and vertical mound sizes as a function of increasing layer thickness.

Both curves show an approximately tenfold decrease in the rms-surface roughness as the growth temperature is raised from 600 to 700 to 800 °C, with \( \sigma \) values decreasing from 8.6 to 3.3 to 0.8 nm for \( t=57 \) nm and 18.8 to 9.3 to 1.1 nm for \( t=230 \) nm.

The plot also contains “selected-area” roughness values \( \alpha_{sa} \) obtained from an analysis where the misoriented grains and the supermounds for layers grown at 600 and 700 °C, respectively, have been excluded. That is, the plotted data corresponds to the roughness of the epitaxial matrix that surrounds the surface protrusions. This surrounding matrix is considerably smoother than the overall surface. For example, the \( \alpha_{sa} = 3.0 \) nm for the 230-nm-thick layer grown at 600 °C is 6 times smaller than the corresponding \( \sigma \) value. Similarly, the surfaces surrounding the supermounds grown at 700 °C are relatively smooth, \( \alpha_{sa} = 0.9 \) and 1.2 nm for \( t=57 \) and 230 nm, respectively, which is almost as low as 0.8 and 1.1 nm, the values for \( T_s=800 \) °C.

The roughening rate during thin-film growth is often described by a power law, \( \sigma \propto t^\beta \), where \( t \) is the layer thickness and \( \beta \) is the roughening exponent.\(^{32,33} \) This relationship has previously been applied to describe the kinetic roughening of epitaxial TiN(001) and CrN(001) layers grown from normal incidence (\( \alpha = 0^\circ \)), yielding roughening exponents of 0.25 and 0.37, respectively.\(^{34,35} \) We determine \( \beta \) values from our roughness data, assuming that the roughening for deposition from oblique angles (\( \alpha = 80^\circ \)) also follows such a power law, (however, with a relatively large uncertainty since each \( \beta \) value is determined from only two data points) and obtain \( \beta = 0.57, 0.76, \) and 0.26 for \( T_s = 600, 700, \) and 800 °C. The corresponding values from the selected-area analysis, as described above, are 0.20 for \( T_s = 600 \) °C and 0.27 for \( T_s = 700 \) °C. These latter values, as well as the \( \beta \) value from the layer grown at 800 °C, are in good agreement with the reported values for TiN(001) and CrN(001). This indicates that the roughening of the epitaxial portion of our layers, as studied using \( \alpha_{sa} \), can be attributed to kinetic roughening, in agreement with the above discussion on surface mound and \langle 110 \rangle-ridge structures that also indicate kinetic roughening.

In contrast, \( \beta \) values for the complete surfaces, that is, including the misoriented grains and supermounds at 600 and 700 °C, are >0.5. We attribute this high roughening rate to atomic shadowing which causes the surface protrusions to have a higher growth rate than the surrounding matrix, leading to an overall high surface roughness. This is consistent with theoretical predictions of the roughening exponent under strong atomic shadowing conditions, with reported \( \beta \) values ranging from 0.56 to 1.00.\(^{36-39} \)

**IV. CONCLUSIONS**

The surface morphology of CrN layers grown on MgO(001) from an oblique deposition angle \( \alpha = 80^\circ \) by ultrahigh vacuum magnetron sputtering exhibits qualitative changes as a function of deposition temperature from 600 to 800 °C. Layers grown at 600 °C consist of an epitaxial matrix that contains misoriented grains which nucleate randomly during layer growth and grow in width as a function of layer thickness to form cone-shaped structures and triangular surface protrusions. Growth at 700 °C leads to single-crystal layers with a surface morphology that is characterized by dendritic ridge patterns extending along the orthogonal \langle 110 \rangle directions superposed by square-shaped supermounds with \langle 100 \rangle edges. The ridge patterns are attributed to a Bales-Zangwill instability while the supermounds form due to atomic shadowing which leads to the formation of epitaxial inverted pyramids that are separated from the surrounding layer by tilted nanovoids. Layers grown at 800 °C are also complete single crystals. Their surfaces are relatively smooth, with ridges elongated along \langle 110 \rangle, indicating a high adatom mobility. The development of the surface roughness is attributed to two distinct mechanisms. Kinetic roughening controls the ridge-pattern formation at \( T_s = 800 \) °C as well as the roughening of the epitaxial matrix at 600 and 700 °C; it is characterized by a growth exponent \( \beta = 0.27 \). In contrast, atomic shadowing results in an exacerbated growth rate of misoriented grains at 600 °C and supermounds at 700 °C, which, in turn, leads to relatively large rms-surface roughness values as well as \( \beta > 0.5 \).

**ACKNOWLEDGMENT**

This research was supported by the National Science Foundation, Division of Manufacturing and Industrial Innovation, under Grant No. DMII-0423358.