University of Groningen

Mound surface roughness effects on the thermal capacitance of thin films

Palasantzas, G.; de Hosson, J. Th. M.

Published in:
Journal of Applied Physics

DOI:
[10.1063/1.1368390](https://doi.org/10.1063/1.1368390)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2001

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Palasantzas, G., & de Hosson, J. T. M. (2001). Mound surface roughness effects on the thermal capacitance of thin films. *Journal of Applied Physics*, 89(11), 6130 - 6134.
<https://doi.org/10.1063/1.1368390>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Mound surface roughness effects on the thermal capacitance of thin films

G. Palasantzas^{a)} and J. Th. M. De Hosson

Department of Applied Physics, Materials Science Centre and Netherlands Institute for Metals Research, University of Groningen, 9747 AG Groningen, The Netherlands

(Received 28 November 2000; accepted for publication 7 March 2001)

We investigate the influence of roughness at a nanometer scale on the thermal properties of thin films. It is shown that the roughness causes an increase of the thermal capacitance. For mound rough surfaces the increase of the thermal capacitance depends strongly on the relative magnitude of the average mound separation λ and the system correlation length ζ . Indeed, a rather complex behavior develops for $\zeta > \lambda$, while for $\zeta < \lambda$ a smooth decrease of the capacitance as a function of the average mound separation λ takes place. Finally, the roughness strongly affects the thermal capacitance as a function of the film thickness as long as $\zeta < \lambda$, while a precise determination of the actual effect requires a more-detailed knowledge of the thickness dependence of the involved roughness parameters during film growth. © 2001 American Institute of Physics. [DOI: 10.1063/1.1368390]

I. INTRODUCTION

Many device geometries require the growth of high-quality films. However, kinetic effects may induce a substantial roughness depending on the material, the substrate, and the deposition conditions. Deviations of surfaces/interfaces from flatness, as well as the presence of material defects (e.g., dislocations, impurities, etc.) may alter the operation characteristics of microelectronic devices.^{1,2} For example, the presence of a rough metal/insulator interface was shown to influence the field breakdown mechanism,³ as well as the capacitance and leakage currents in thin-film capacitors.⁴ Random rough surfaces have been shown to affect the image potential of a charge situated in the vicinity of the vacuum/dielectric interface.⁵ Such roughness effects could have a strong influence on inversion layers at the semiconductor/oxide interface, because they cause a shift of electronic levels⁵ and, consequently, alter the device operation. In addition, surface/interface roughness has been shown to influence strongly the electrical conductivity of semiconducting and metallic thin films.⁶

In contrast to electric transport properties, only a small amount of progress has been achieved for roughness effects on thermal transport properties in thin films. Indeed, the topic of thermal management issues in electronic and optical devices has been a topic of intense research in recent years.⁷⁻¹⁰ For example, the lifetime of metallic interconnects in integrated circuits depends strongly on the operating temperature because the resistive heating increases their temperature. In photothermal analyses,¹¹ Au films are deposited on dielectric substrates for heat adsorption because their properties are necessary for deducing the thermal properties of the dielectric film. It appears that the thermal conductivity of thin films (thickness $h_0 < 1000$ nm) is less than its bulk value due to surface and grain-boundary scattering mechanisms.^{11,12} Although much work has been concen-

trated on the effect of film thickness on thermal conductivity, only recently the effect of surface roughness and film microstructure was investigated in order to understand the thermal conductivity results.⁷ It was found that roughness development yielded a lower thermal conductivity, with the film texture also playing a significant role.⁷

Furthermore, during epitaxial growth of thin films the growth front can be rough in the sense that multilayer step structures are formed.^{13,14} In this case, the existence of an asymmetric step-edge diffusion barrier (Schwoebel barrier) inhibits the down-hill diffusion of incoming atoms, leading effectively to the creation of multilayer step structures in the form of mounds (unstable growth).^{13,14} So far, a theoretical investigation of the mound surface roughness, and more general thin-film growth mechanisms, on thermal properties remains widely unexplored, and will be the topic of the present work.

II. THERMAL FIELD AND CAPACITY CALCULATION FOR A FILM WITH A SINGLE ROUGH BOUNDARY

A. Thermal field calculation

Consider a film with its rough surface at temperature T_2 and its smooth one (film/substrate interface) at temperature T_1 , as is shown in Fig. 1. In order to calculate the temperature distribution under steady heat flow conditions ($\partial T / \partial t = 0$), one needs to solve the Laplace equation¹ for film thickness varying between $z = 0$ and $z = f(x, y)$:

$$\nabla^2 T(x, y, z) = 0, \quad (1)$$

and boundary conditions

$$T(x, y, z = 0) = T_1 \wedge T[x, y, z = f(x, y)] = T_2, \quad (2)$$

where $T(x, y, z)$ is the temperature distribution, and $z = f(x, y)$ is the rough film surface. Assuming $f(x, y) = h_0 + \lambda h(x, y)$, we can apply a perturbation theory to solve Eq. (1) by expanding Eq. (2) and $T(x, y, z)$ in Taylor series of the form

^{a)} Author to whom correspondence should be addressed; electronic mail: g.palasantzas@phys.rug.nl

FIG. 1. Schematic of a film with a single rough boundary (film surface) and a smooth film/substrate interface.

$$T(x, y, h_0) + T_z(x, y, h_0) \lambda h(x, y) + \frac{1}{2!} T_{zz}(x, y, h_0) \lambda^2 h^2(x, y) + \dots = T_2, \quad (3)$$

$$T(x, y, z) = T^{(0)}(x, y, z) + \lambda T^{(1)}(x, y, z) + \lambda^2 T^{(2)}(x, y, z) + \dots \quad (4)$$

For the zero-order term $T^{(0)}(x, y, z)$, the boundary conditions $T^{(0)}(x, y, z=0) = T_1$ and $T^{(0)}(x, y, z=h_0) = T_2$ yield the solution $T^{(0)}(x, y, z) = (z/h_0)(T_2 - T_1)$. For first- and second-order terms $T^{(n)}(x, y, z)$ ($n \geq 1$) we have, respectively,

$$T^{(1)}(x, y, z=0) = 0 \wedge T^{(1)}(x, y, z=h_0) = -h(x, y) T_z^{(0)}(x, y, h_0), \quad (5)$$

$$T^{(2)}(x, y, z=0) = 0 \wedge T^{(2)}(x, y, z=h_0) = -h(x, y) T_z^{(1)}(x, y, h_0) - \frac{1}{2} h^2(x, y) T_{zz}^{(0)}(x, y, h_0). \quad (6)$$

Further, the Fourier transform technique is employed to solve the Laplace equations $\nabla^2 T^{(n)}(x, y, z) = 0$ ($n \geq 1$), which are obtained by substituting Eq. (4) into Eq. (1). Setting $\lambda=1$ in Eq. (4) and using Eqs. (A3)–(A4) from the Appendix, we obtain

$$\begin{aligned} T(x, y, z) \approx & \frac{(T_2 - T_1)}{h_0} z \\ & - \frac{(T_2 - T_1)}{h_0} \int dk \frac{\sinh(kz)}{\sinh(kh_0)} \tilde{h}(k) e^{-ik\rho} \\ & + \frac{(T_2 - T_1)}{h_0} \int dk \int dk' \\ & \times \frac{\cosh(k'h_0) \sinh(kz)}{\sinh(k'h_0) \sinh(kh_0)} \\ & \times k' \tilde{h}(k') \tilde{h}(k-k') e^{-ik\rho}. \end{aligned} \quad (7)$$

B. Thermal capacitance calculation

The specific thermal capacitance (for constant volume) “ c ” is given by the energy balance equation

$$Vc(T_2 - T_1) = K_{\text{thc}} t \int (-\nabla T \cdot \hat{n}) dS, \quad (8)$$

with $\hat{n} = (\nabla h - \hat{z})/[1 + (\nabla h)^2]^{1/2}$ the unit vector normal to the surface, K_{thc} the thermal conductivity, $dS = \sqrt{1 + (\nabla h)^2} d^2\rho$ the differential area, t the time that the heat flux is passing through the film, and V the film volume. Note that $-\nabla T$ represents the thermal field that drives heat flow, and $K_{\text{thc}}(-\nabla T \cdot \hat{n})$ the heat density on the rough film surface.

Assuming statistically stationary surfaces up to the second order (translation invariant), the average over possible roughness configurations can be expressed as $\langle \tilde{h}(k) \tilde{h}(k') \rangle = [(2\pi)^4/A] \langle |\tilde{h}(k)|^2 \rangle \delta(k+k')$, where A is the average flat macroscopic surface area. For small surface roughness or $|\nabla h| \ll 1$ ($dS \approx [1 + (1/2)(\nabla h)^2] d^2\rho$), we obtain from Eqs. (8) and (7), and taking into account $\langle \tilde{h}(\mathbf{k}) \rangle = 0$, the average thermal capacitance

$$\langle c \rangle = \langle c_0 \rangle M(h_0), \quad c_0 = \frac{K_{\text{thc}} t}{h_0^2}, \quad (9)$$

where

$$\begin{aligned} M(h_0) = & \left\{ 1 + \frac{(2\pi)^4}{A} \left[2 \int_{0 < k < k_c} k^2 \langle |\tilde{h}(k)|^2 \rangle d^2k \right. \right. \\ & \left. \left. + \frac{2\pi}{h_0} \int_{0 < k < k_c} \frac{\cosh(kh_0)}{\sinh(kh_0)} k \langle |\tilde{h}(k)|^2 \rangle d^2k \right] \right\}, \end{aligned} \quad (10)$$

with $K_c = \pi/a_0$ and a_0 a lower roughness cutoff of the order of the atomic spacing, and film volume $V \approx Ah_0$.

III. MOUND ROUGH MORPHOLOGY

Mound rough surfaces have been described in the past by the interface width w ; the system correlation length ξ , which defines the randomness of the mound distribution on the surface; and the average mound separation λ .¹⁴ Such a rough morphology can be described by the height–height correlation function $C(r) = \langle h(r)h(0) \rangle = w^2 e^{-(r/\xi)^2} J_0(2\pi r/\lambda)$, where its Fourier transform is of the form¹⁴

$$\langle |\tilde{h}(k)|^2 \rangle = \frac{A}{(2\pi)^5} \frac{w^2 \xi^2}{2} e^{-(4\pi^2 + k^2 \lambda^2)(\xi^2/4\lambda^2)} I_0(\pi k \xi^2/\lambda), \quad (11)$$

with $\tilde{h}(k)$ the Fourier transform of $h(r)$. $J_0(x)$ and $I_0(x)$ are, respectively, the Bessel and modified Bessel function of the first kind and zero order. If $\xi \gg \lambda$, the surface is characteristic of that caused by Schwoebel barrier effects.¹⁴ Note that the correlation function $C(r)$ of the mound roughness has an oscillatory behavior for $\xi \gg \lambda$, which leads to a characteristic satellite ring at $k = 2\pi/\lambda$ of the power spectrum $\langle |\tilde{h}(k)|^2 \rangle$.¹⁴

FIG. 2. rms local surface slope $\rho_{\text{rms}} = \langle |\nabla h|^2 \rangle^{1/2}$ as a function of the average mound separation λ for various system correlation lengths ζ , $w = 1$ nm and $a_0 = 0.3$ nm.

IV. THERMAL CAPACITANCE DEPENDENCE ON MOUND ROUGHNESS

Our calculations have been performed for small roughness ($|\nabla h| < 1$) or alternatively small rms local surface slopes $\rho_{\text{rms}} = \langle |\nabla h|^2 \rangle^{1/2} < 1$, and small rms roughness amplitudes $w \ll h_0$. Figure 2 shows the dependence of the local surface slope as a function of the average mound separation λ for various system correlation lengths ζ . The local surface slope is given by $\rho_{\text{rms}} = \{[(2\pi)^4/A] \times \int_0 < k < k_c k^2 \langle |h(k)|^2 \rangle d^2 k\}^{1/2}$, which is essentially proportional to the second term in Eq. (10). For system correlation lengths $\zeta > \lambda$, the local surface slope decays in an oscillatory fashion as λ increases (or the ratio w/λ decreases leading to surface smoothing). On the other hand for $\zeta < \lambda$, the local slope decays exponentially as the surface smoothens or w/λ decreases.

Since $\langle |h(k)|^2 \rangle \propto w^2$, the thermal capacitance will have a simple dependence on the roughness amplitude w , while any complex dependence will arise as a function of the lateral length scales ζ and λ through the factor $M(h_0)$. Figure 3 shows the dependence of the thermal capacitance ratio $\langle c \rangle / c_0$ as a function of the average mound separation λ . At any rate, $\langle c \rangle \geq c_0$, or in other words, the presence of roughness increases the thermal capacitance.

Upon increasing λ (or decreasing w/λ), i.e., surface smoothing at larger wavelengths, $\langle c \rangle$ approaches the thermal capacitance c_0 characteristic for a film with a flat sur-

FIG. 3. Thermal capacitance ratio $\langle c \rangle / c_0$ as a function of the average mound separation λ for various system correlation lengths ζ , $w = 1$ nm, $h_0 = 30$ nm, and $a_0 = 0.3$ nm.

FIG. 4. Thermal capacitance ratio $\langle c \rangle / c_0$ as a function of the system correlation length ζ for various average mound separations λ , $w = 1$ nm, $h_0 = 30$ nm, and $a_0 = 0.3$ nm.

face. However, for large system correlation lengths such that $\zeta > \lambda$, significant increments of $\langle c \rangle$ develop, approaching finally c_0 for large mound separations $\lambda (> \zeta)$. Such an effect is special for mound roughness, while for any other type of roughness, such as Gaussian or self-affine fractal roughness, a smooth approach to the thermal capacitance for films with flat boundaries will eventually occur (similarly to the case of $\lambda \gg \zeta$). Such an effect reflects the oscillatory behavior of the height-height correlation function for mound roughness that takes place for $\zeta > \lambda$.¹⁴ Finally, the thermal capacitance shows a complex behavior as a function of the system correlation length ζ (Fig. 4), i.e., with a smooth decrement towards its value for films with flat boundaries as long as λ is small ($< \zeta$). For intermediate values of the average mound separation a complex behavior develops, as is displayed in Fig. 4.

Note that if in Eq. (10) the integration is extended to infinity ($K_c \zeta, K_c \lambda \gg 1$), we obtain a simpler thermal capacity expression

$$\begin{aligned} \langle c \rangle = c_0 & \left[1 + w^2 \left(\frac{1}{\zeta^2} + \frac{\pi^2}{\lambda^2} \right) \right. \\ & + \frac{(2\pi)w^2\zeta^2 e^{-(\pi^2\zeta^2/4\lambda^2)}}{2h_0} \int_0^\infty k^2 \frac{\cosh(kh_0)}{\sinh(kh_0)} \\ & \left. \times e^{-k^2\zeta^2/4} I_0(\pi k\zeta^2/\lambda) dk \right], \end{aligned} \quad (12)$$

with the third term in the parenthesis of Eq. (12) becoming insignificant with increasing film thickness h_0 .

Finally, we will investigate roughness effects on the thermal capacitance as a function of the film thickness. Figure 5 shows the dependence of $\langle c \rangle / c_0$ on film thickness h_0 . The ratio $\langle c \rangle / c_0$ decreases drastically for small system correlation lengths ($\zeta < \lambda$), which can be understood from Eq. (12) due to its Gaussian dependence on the ratio ζ/λ . A more precise determination of the film thickness effect needs a more precise knowledge of the dependence of the roughness parameters (w, ζ, λ) on film thickness. For example, the average mound separation has been shown to evolve with film thickness (or growth time for fixed deposition rate) as $\lambda \propto h_0^\beta$ ($0.16 \leq \beta \leq 0.26$),¹³ and the rms roughness amplitude as

FIG. 5. Thermal capacitance ratio $\langle c \rangle / c_0$ as a function of the film thickness for various system correlation lengths ζ . The inset shows a similar plot for various average mound separations λ . $w = 1$ nm, and $a_0 = 0.3$ nm for both plots.

$w \propto h_0^{\beta'}$ ($\beta' < 1$).¹⁴ As an example, we consider in Fig. 6 the thickness dependence of the ratio $\langle c \rangle / c_0$ for growth with roughness parameters evolving with a film thickness h_0 as $w = 1.0(h/10)^{0.24}$ (nm), $\lambda = 10(h/10)^{\beta}$ (nm), and $\zeta = 20(h/10)^{\beta}$ (nm). As Fig. 6 indicates, different growth exponents β have a strong contribution on the thermal capacitance ratio $\langle c \rangle / c_0$ as a function of the film thickness h_0 .

For the actual dependence of the average thermal capacitance $\langle c \rangle$ on thickness, one has also to consider the thickness dependence of the thermal conductivity K_{the} . Indeed, for sufficiently thick films this is given by $K_{\text{the}} = K_{\text{bulk}} / [1 + (3L/8h_0) + (7G/5)]$,^{7,12} with K_{bulk} the bulk thermal conductivity, L the electron mean-free path [i.e., $L \sim 41$ nm for Au (Ref. 7)], and $G = (L/h_0)[R/(1-R)]$ with R the electron reflection coefficient due to scattering at grain boundaries for the more general case of polycrystalline films. This equation for K_{the} is valid if $G < 10$ and $L/h_0 > 0.1$,⁷ and incorporates both surface and grain-boundary electron scattering in a quasiclassical sense. Its derivation is based on the electrical conductivity via the use of the Wiedemann–Franz law (assuming that electrons serve both as electrical and thermal carriers with phonons having a negligible effect on the thermal conductivity of metals⁷). Such a law was discovered initially for bulk materials, and has been proven to be valid also for thin

FIG. 6. Thermal capacitance ratio $\langle c \rangle / c_0$ as a function of the film thickness for the film with the roughness parameters evolving with thickness as $w = 1.0(h/10)^{0.24}$ (nm), $\lambda = 10(h/10)^{\beta}$ (nm), and $\zeta = 20(h/10)^{\beta}$ (nm). The curves correspond to different growth exponents β .

films.¹⁰ In contrast, for ultrathin films ($h_0 < 10$ nm) one has to consider quantum size effect contributions to the thermal conductivity.⁶

V. CONCLUSIONS

In summary, we investigated the effect of roughness on the thermal capacitance of thin films with one smooth boundary and the other rather rough at a nanometer-length scale. Qualitatively, similar results would be expected for films with double rough boundaries, as well as for other geometries. It is found that the roughness may cause a strong increase of the thermal capacitance. For mound rough surfaces such an increase strongly depends on the relative magnitude of the average mound separation λ and the system correlation length ζ . Indeed, complex behavior develops for $\zeta > \lambda$, while a smooth decrease of the thermal capacitance as a function of λ occurs for $\zeta < \lambda$ (Gaussian-type behavior of boundary roughness). Finally, as a function of film thickness the thermal capacitance decreases with roughness, contributing significantly to small film thickness as long as $\zeta < \lambda$. At any rate, a precise determination of the actual effect will require a detailed knowledge of the thickness dependence of the roughness parameters during film growth.

ACKNOWLEDGMENTS

The authors would like to acknowledge support from the “Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO),” as well as useful discussions with Y.-P. Zhao (Rensselaer Polytechnic Institute).

APPENDIX

Here, we outline the Fourier analysis procedure.⁴ Indeed, we have to solve the Laplace equations

$$\nabla^2 T^{(n)}(x, y, z) = T_{zz}^{(n)}(x, y, z) + \nabla_{\rho}^2 T^{(n)}(x, y, z) = 0 \quad (n=1, 2), \quad (\text{A1})$$

with $\rho = (x, y)$ representing the position vector in the x - y plane. Performing a Fourier transform in the x - y plane according to the equations $\tilde{\Phi}^{(n)}(k, z) = [1/(2\pi)^2] \int d\rho \times T^{(n)}(\rho, z) e^{ik \cdot \rho}$, $T^{(n)}(\rho, z) = \int dk \tilde{\Phi}^{(n)}(k, z) e^{-ik \cdot \rho}$, the Laplace Eq. (A1) takes the form $\tilde{\Phi}_{zz}^{(n)}(k, z) - k^2 \tilde{\Phi}^{(n)}(k, z) = 0$, which has the general solution

$$\tilde{\Phi}^{(n)}(\mathbf{k}, z) = 2A^{(n)}(\mathbf{k}) \sinh(kz), \quad (\text{A2})$$

under the constraint that $\tilde{\Phi}^{(n)}(k, z)|_{z=0} = 0$ for $z=0$ [since $T^{(n)}(\rho, z=0) = 0$]. The coefficients $A^{(n)}(\mathbf{k})$ can be determined by the boundary condition at $z = h_0$ [Eqs. (5) and (6)].

For the first-order perturbation, we obtain in Fourier space $\tilde{\Phi}^{(1)}(k, z) = -(T_2 - T_1/h_0)[\sinh(kz)/\sinh(kh_0)]\tilde{h}(k)$, and in real space

$$T^{(1)}(\rho, z) = -\frac{(T_2 - T_1)}{h_0} \int dk \frac{\sinh(kz)}{\sinh(kh_0)} \tilde{h}(k) e^{-ik \cdot \rho}. \quad (\text{A3})$$

Similarly, for the second-order perturbation we obtain $\tilde{\Phi}^{(2)}(k, z) = [(T_2 - T_1)/h_0] \int dk' [\cosh(k'h_0) \sinh(kz)/\sinh(k'h_0)]$

$\times \sinh(kh_0)]k'\tilde{h}(k')\tilde{h}(k-k')$ by using the property of convolution for the Fourier transform. Thus, in real space we have

$$T^{(2)}(\mathbf{p}, z) = \frac{(T_2 - T_1)}{h_0} \int dk \int dk' \times \frac{\cosh(k'h_0)\sinh(kz)}{\sinh(k'h_0)\sinh(kh_0)} k'\tilde{h}(k')\tilde{h}(k-k') \times e^{-ik \cdot \mathbf{p}}. \quad (\text{A4})$$

¹S. M. Sze, *Semiconductor Devices: Physics and Technology* (Wiley, New York, 1985).

²K. A. McKinley and N. P. Sandler, *Thin Solid Films* **290**, 440 (1996).

³J. H. Oh, Y. H. Lee, B. K. Ju, D. K. Shin, C. Y. Park, and M. H. Oh, *J. Appl. Phys.* **82**, 6203 (1997).

⁴Z. P. Zhao, G.-C. Wang, T.-M. Lu, G. Palasantzas, and J. Th. M. De Hosson, *Phys. Rev. B* **60**, 9127 (1999).

⁵T. S. Rahman and A. A. Maradudin, *Phys. Rev. B* **21**, 504 (1980); G. Palasantzas, *J. Appl. Phys.* **82**, 351 (1997); F. J. Ohkawa and Y. Uemura, *Prog. Theor. Phys.* **57**, 164 (1975); T. Ando, *J. Phys. Soc. Jpn.* **39**, 411 (1975).

⁶T. Ando, A. B. Fowler, and F. Stern, *Rev. Mod. Phys.* **54**, 437 (1982); A. Hartstein, T. H. Ning, and A. B. Fowler, *Surf. Sci.* **58**, 178 (1976); T.

Ando, *J. Phys. Soc. Jpn.* **51**, 3900 (1982); G. Fishman and D. Calecki, *Phys. Rev. Lett.* **62**, 1302 (1989); G. Fishman and D. Calecki, *Phys. Rev. B* **43**, 11581 (1991); H. Sakaki, T. Noda, K. Hirakawa, M. Tanaka, and T. Matsusue, *Appl. Phys. Lett.* **51**, 1934 (1987); G. Palasantzas and J. Barnas, *Phys. Rev. B* **56**, 7726 (1997); G. Palasantzas and J. Barnas, *Phys. Status Solidi B* **209**, 319 (1998); J. Barnas and G. Palasantzas, *J. Appl. Phys.* **82**, 3950 (1997).

⁷G. Chen and P. Hui, *Appl. Phys. Lett.* **74**, 2942 (1999).

⁸J. C. Lambropoulos, S. D. Jacobs, S. J. Burns, L. Shaw-Klein, and S.-S. Hwang, *Thin Film Heat Transfer: Properties and Processing* (ASME, New York, 1991), Vol. **184**, p. 21.

⁹T. Yamane, Y. Moi, S. Katayama, and M. Todoki, *J. Appl. Phys.* **82**, 1153 (1997).

¹⁰T. Startz, U. Schmidt, and F. Volklein, *Science Technol. (USA)* **7**, 395 (1995).

¹¹Z. L. Wu, P. K. Kuo, L. Wei, S. L. Gu, and R. L. Thomas, *Thin Solid Films* **236**, 191 (1993).

¹²T. Q. Qui and C. L. Tien, *Trans. ASME* **115**, 842 (1993).

¹³M. D. Johnson, C. Orme, A. W. Hunt, D. Graff, J. Sudijono, L. M. Sander, and B. G. Orr, *Phys. Rev. Lett.* **72**, 116 (1994); M. Siegert and M. Plischke, *ibid.* **73**, 1517 (1994); J.-K. Zuo and J. F. Wendelken, *ibid.* **78**, 2791 (1997); J. A. Strosio, D. T. Pierce, M. D. Stiles, A. Zangwill, and L. M. Sander, *ibid.* **75**, 4246 (1995).

¹⁴Y.-P. Zhao, H.-Y. Yang, G. C. Wang, and T.-M. Lu, *Phys. Rev. B* **57**, 1922 (1998).