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Double in-plane alignment in biaxially textured thin films

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The scientific interest and technological relevance of biaxially textured polycrystalline thin films stem from their microstructure that resembles that of single crystals. To explain the origin and predict the type of biaxial texture in off-normally deposited films, Mahieu *et al.* have developed an analytical model [S. Mahieu *et al.*, Thin Solid Films **515**, 1229 (2006)]. For certain materials, this model predicts the occurrence of a double in-plane alignment, however, experimentally only a single in-plane alignment has been observed and the reason for this discrepancy is still unknown. The model calculates the resulting in-plane alignment by considering the growth of faceted grains with an out-of-plane orientation that corresponds to the predominant film out-of-plane texture. This approach overlooks the fact that in vapor condensation experiments where growth kinetics is limited and only surface diffusion is active, out-of-plane orientation selection is random during grain nucleation and happens only upon grain impingement. Here, we compile and implement an experiment that is consistent with the key assumptions set forth by the in-plane orientation selection model by Mahieu *et al.*; a Cr film is grown off-normally on a fiber textured Ti epilayer to pre-determine the out-of-plane orientation and only allow for competitive growth with respect to the in-plane alignment. Our results show unambiguously a biaxially textured Cr (110) film that possesses a double in-plane alignment, in agreement with predictions of the in-plane selection model. Thus, a long standing discrepancy in the literature is resolved, paving the way towards more accurate theoretical descriptions and hence knowledge-based control of microstructure evolution in biaxially textured thin films. © 2014 AIP Publishing LLC.

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Biaxially textured polycrystalline thin films consist of grains that are preferentially aligned both out-of-plane (perpendicular to the substrate surface) as well as in-plane (parallel to the substrate surface). The latter results in formation of low energy grain boundaries, which leads to a microstructure that resembles that of single crystals.¹ This makes biaxially textured films suitable as buffer layers for highly oriented superconducting^{1–3} and semiconducting^{4–6} films.

The majority of polycrystalline films are today synthesized by vapor condensation with the vapor flux typically arriving parallel with respect to the substrate surface normal at kinetically limited growth conditions.⁷ This leads to nucleation of atomic islands with random out-of-plane and in-plane alignments as long as no epitaxial relationship exists between deposit and substrate.⁸ As islands grow in size they start to impinge on each other which, at conditions (e.g., substrate temperature) that only allow for surface diffusion to be active (also referred to as zone T conditions⁹), initiates a competitive growth process. In this process, islands with the surface that offers the longest adatom residence time, i.e., lowest diffusivity, have a higher probability to trap adatoms that diffuse on both sides of a grain boundary.^{10,11} Those islands thus capture more adatoms and overgrow all other islands. This leads to the development of a preferred out-of-plane orientation, while leaving the in-plane orientation

unaffected, i.e., random. Such films are referred to as being fiber textured.

Deposition at an angle other than zero with respect to the substrate surface normal (referred to as off-normal growth or inclined substrate deposition) leads to a directional three-dimensional (3D) net flux of vapor and a two-dimensional (2D) net flux of adatoms on the surface of the growing film. The latter flux arises since adatoms preserve their momentum component along the substrate surface, and thus possess a preferred diffusion direction.^{12,13} Both 3D and 2D net fluxes have been suggested to cause a preferred in-plane alignment due to differences in the adatom capture cross sections that different in-plane oriented islands exhibit.^{9,14,15} However, the capture of the 2D flux is believed to be the main mechanism that determines the in-plane grain orientation.^{9,16–18}

To explain the occurrence and predict the type of biaxial texture arising from the directed 2D adatom flux, Mahieu *et al.*⁹ developed a model that calculates the 2D flux capture cross section—referred to as capture length—for grains with different in-plane orientations. These calculations consider a single adatom diffusion direction and a faceted crystal of a given out-of-plane orientation that is rotated around its out-of-plane normal to yield different in-plane orientations.^{9,17,18} The orientation that maximizes the capture length should capture more adatoms and overgrow all others.^{9,17,18} Capture length calculations for grains with certain combinations

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of out-of-plane and facets orientations, e.g., an [111] out-of-plane oriented cubic crystal with {100} facets, have predicted that two different in-plane alignments possess the same maximum capture length.⁹ This means that two different in-plane alignments, with the same out-of-plane orientation, are predicted to concurrently evolve. However, in all experimental reports on films with the above-mentioned orientation and facets, such as MgO and TiN, only one of the predicted in-plane alignments is observed.^{9,19–21} Double in-plane alignment has only been reported by Deng *et al.*²² for AlN films grown at a vapor flux incidence angle of 45° which changes into a single in-plane alignment for larger vapor incident angles. The reason for the discrepancy between experimental data and model predictions is still unknown.

The model developed by Mahieu *et al.*⁹ calculates the capture length and predicts the type of in-plane alignment by considering only grains that exhibit an out-of-plane alignment that corresponds to the dominant out-of-plane texture. This means that the effect of differently out-of-plane oriented grains on in-plane orientation selection during island growth, impingement, and competitive growth is not taken into account. In this letter, we compile and implement an experimental strategy which yields growth conditions that are consistent with the main assumptions of the in-plane orientation selection model. This is achieved by the off-normal growth of a Cr film on a fiber textured Ti epilayer to select the film out-of-plane orientation while maintaining a random in-plane alignment during nucleation. Our results reveal a double in-plane alignment, which is shown to be consistent with capture length calculations performed here following the procedure proposed by Mahieu *et al.*⁹ This is to be compared with Cr grown on Si substrates where a single in-plane alignment is obtained, even though capture length calculations yield qualitatively similar predictions as those in the case of the Cr film grown on the Ti epilayer.

Films were grown in a vacuum chamber with a base pressure of 8×10^{-6} Pa on Si (100) substrates with a native SiO₂ layer. Two magnetrons were used for the depositions, where one was facing the substrate and the other was positioned perpendicular to the substrate surface normal. A circular Ti target with a diameter of 50.8 mm was mounted on the former magnetron and an identically sized Cr target on the latter one. The target-to-substrate distance was ~ 90 mm in both cases. Argon was used as sputtering gas at a pressure of 0.67 Pa to grow films using direct current magnetron sputtering (MDX 1 K, Advanced Energy). Average powers of 100 and 150 W were employed for Ti and Cr, respectively. Cr films with a thickness of ~ 1 μ m were grown at otherwise identical deposition conditions either onto the Si substrates or on a ~ 120 nm Ti epilayer that was deposited on the Si substrates prior to the Cr film. X-ray diffractometry (XRD, Philips X'Pert) was used to study the film texture (using pole figure measurements), while transmission electron microscopy (TEM, FEI Tecnai G2) was utilized to study the film microstructure.

Figures 1(a) and 1(b) show cross-sectional TEM micrographs of Cr films with and without the Ti layer, respectively. In both films, a columnar microstructure is observed in which columns are tilted towards the direction of the

vapor source in agreement with a previous work of ours.²³ Intra-columnar voids are also observed at larger thicknesses in both films (see insets in Figs. 1(a) and 1(b)), which is indicative of a limited surface diffusion.^{24,25} High resolution TEM of the Cr/Ti interface in Fig. 1(c) shows that Cr grows epitaxially on the Ti layer and the epitaxial relationship is determined to be Cr(110)//Ti(0002),²⁶ which is observed consistently along the interface. Note that this yields domain epitaxy²⁷ in the Cr[1 $\bar{1}$ 0]/Ti[1 $\bar{1}$ 00] directions where the position of every fifth Cr atom matches that of every fourth Ti atom. The evolution of the selected area electron diffraction patterns for the same two Cr films is shown in Figs. 1(d)–1(g). The diffraction patterns from just above the Cr/Ti (d) and Cr/Si (f) interfaces show three discontinuous and distinct rings, corresponding to Cr (110), (200), and (211). For the epitaxially grown Cr film, this indicates grains that are oriented randomly only in-plane,²⁸ which is consistent with the fact that the Ti epilayer is fiber textured.²⁶ In the case of the Cr film grown directly on the SiO₂/Si substrate, the rings signify randomly in-plane and out-of-plane oriented islands during nucleation, which is expected for metals growing on amorphous SiO₂ substrates.⁸ At higher thicknesses, the selected area diffraction patterns change into discrete spots (see Figs. 1(e) and 1(g)), which means that some grains are overgrown by others in a competitive growth process.

To evaluate the texture arising from this overgrowth we recorded XRD pole figures, by varying the sample tilt angle ψ and the rotation angle ϕ for a given (*hkl*) reflection. The (110) and (200) pole figures for the Cr film grown on the Ti epilayer are shown in Figs. 2(a) and 2(b), respectively. Four elongated poles positioned at $\psi \sim 60^\circ$ and $\phi \sim 40^\circ, 140^\circ, 220^\circ$, and 320° are seen to surround a central pole in the (110) pole figure. This means that the film is biaxially

FIG. 1. Cross-sectional TEM micrographs corresponding to Cr films grown (a) on a fiber textured Ti epilayer and (b) directly on a SiO₂/Si substrate. (c) High resolution TEM of the Cr/Ti interface in (a) with indicated out-of-plane orientations.²⁶ (d) and (e) Selected area electron diffraction patterns of the Cr film in (a), and (f) and (g) show the same for the film in (b).

FIG. 2. Pole figures corresponding to Cr (a) (110) and (b) (200) planes for a Cr film grown on a fiber textured Ti epilayer. The poles corresponding to the more ($n = 0^\circ$) and less ($n = 90^\circ$) intense poles are marked with yellow squares and red dots, respectively. The flux direction is indicated by the arrow.

textured with a [110] out-of-plane orientation, which is consistent with the out-of-plane orientation determined by TEM (see Fig. 1(c)). The (200) pole figure shows four poles positioned at $\psi \sim 45^\circ$ and $\phi \sim 0^\circ, 90^\circ, 180^\circ$, and 270° , where the intensity of the two poles at $\phi \sim 90^\circ$ and 270° is $\sim 40\%$ of the other two. For films with body-centered-cubic (bcc) crystal structure that exhibit a biaxial texture with a [110] out-of-plane orientation the (110) pole figure is expected to consist of five poles, one central pole surrounded by four poles positioned at $\psi = 60^\circ$ and $\phi = n + 55^\circ, n + 125^\circ, n + 235^\circ$, and $n + 305^\circ$, where n is an angle that depends on the in-plane alignment.²⁶ The corresponding (200) pole figure should then consist of two oppositely positioned poles at $\psi = 45^\circ$ and $\phi = n + 0^\circ$ and $n + 180^\circ$.²⁶ Here, $n = 0^\circ$ is defined to correspond to a projected [110] out-of-plane oriented crystal aligned with its long diagonal perpendicular to the flux direction as depicted at the bottom of Fig. 2.²⁶ Accordingly, $n = 90^\circ$ corresponds to the same rhomb-shaped projected crystal aligned with its short diagonal perpendicular to the flux direction (also depicted at the bottom of Fig. 2). Comparing the expected positions of the two (200) poles with the four found experimentally in Fig. 2(b), it is evident that two different in-plane alignments, rotated 90° with respect to each other, are present within the film. The more intense poles in the (200) pole figure correspond to $n = 0^\circ$ and are marked with yellow squares, while the less intense poles correspond to $n = 90^\circ$ and are marked with red dots. The equivalent positions of the four (110) poles at $\psi = 60^\circ$ in Fig. 2(a) are also marked with yellow squares ($n = 0^\circ$) and red dots ($n = 90^\circ$).

For the Cr film grown directly onto the Si substrates, the Cr (110) and (200) XRD pole figures are shown in Figs. 3(a) and 3(b), respectively. Three poles positioned at $\psi \sim 35^\circ$ and $\phi \sim 90^\circ, 210^\circ$, and 330° are seen in the (110) pole figure. The same number of poles are also seen in the (200) pole figure, but instead positioned at $\psi \sim 55^\circ$ and $\phi \sim 30^\circ, 150^\circ$, and 270° . The positions of these poles correspond to a biaxially textured [111] out-of-plane oriented film with a single in-plane alignment, in which the long diagonal of the projected [111] out-of-plane oriented crystal is perpendicular to the flux direction.²⁶ The projected crystal is depicted at

FIG. 3. Pole figures corresponding to Cr (a) (110) and (b) (200) planes for a Cr film grown directly on a SiO_2/Si substrate. Poles corresponding to the favored in-plane alignment are marked with green triangles. The flux direction is indicated by the arrow.

the bottom of Fig. 3 and the expected pole positions are marked with green triangles in the corresponding pole figures. This alignment is in agreement with previous reports for Cr (Ref. 29) and Mo (Ref. 30) films.

To compare our experimental findings with the model by Mahieu *et al.*,⁹ we calculated the capture cross sections of [110] and [111] out-of-plane oriented crystals with {110} facets—the latter is the expected termination for bcc crystals⁹—towards the directed 2D adatom flux. The 2D capture length calculation for the [110] out-of-plane oriented crystal at different in-plane alignments ω is plotted in Fig. 4 (solid black line). Schematic representations of the rhomb-shaped crystal projection²⁶ on the (110) plane for $\omega = 0^\circ, 90^\circ$, and 180° are also depicted above the plot. At these angles, the capture length exhibits maxima, where the maxima at $\omega = 0^\circ$ and 180° correspond to the same in-plane alignment due to crystal symmetry. It is also seen that the maximum at $\omega = 90^\circ$ exhibit $\sim 70\%$ of the value at $\omega = 0^\circ$, i.e., the latter in-plane orientation is more favored. A qualitative comparison with the positions of the poles of the [110]

FIG. 4. Capture length calculation of a [110] out of plane oriented crystal with {110} facets as a function of the in-plane alignment ω (solid black line), and the normalized intensity of the different in-plane alignments as extracted from the Cr (200) pole figure (Fig. 2(b)) for $\psi = 45^\circ$ and $\phi = 180^\circ - 360^\circ$ (dashed blue line). The corresponding in-plane alignments of the projected crystal are depicted above the plot. Yellow squares and red dots correspond to more and less favored in-plane alignments, respectively, as observed in Fig. 2.

out-of-plane oriented Cr film (Fig. 2) reveal that the more intense poles ($n = 0^\circ$, marked with yellow squares) correspond to the more favored alignment in the capture length calculations ($\omega = 0^\circ$). The same is also true for the less intense poles ($n = 90^\circ$, marked with red dots), which correspond to the less favored in-plane alignment ($\omega = 90^\circ$). In order to better illustrate this, the intensities of the two different in-plane alignments were extracted from the Cr (200) pole figure (Fig. 2(b)), where the two orientations are easily distinguished for $\psi = 45^\circ$ in the range $\phi = 180^\circ - 360^\circ$ (or correspondingly $\phi = 0^\circ - 180^\circ$, which yields equivalent in-plane alignments). The normalized intensity is represented by the dashed blue line in Fig. 4, where it can be seen that the plot of the experimentally obtained in-plane alignment follow the same trend and behaviour as that predicted by capture length calculations. Thus, the existence of a double in-plane alignment in a Cr film grown on a fiber textured Ti epilayer corroborates the in-plane selection model proposed by Mahieu *et al.*,⁹ assuming only competitive growth with respect to the in-plane alignment. Moreover, the evolution of the selected area diffraction patterns of the Cr/Ti film (Figs. 1(d) and 1(e)) show that the in-plane alignment does not evolve directly at the interface. This suggests that capture of the directed 3D vapor flux is also relevant for determining the in-plane alignment. For this reason, we also calculated the 3D capture cross section of the [110] out-of-plane oriented crystal.²⁶ The calculation shows the same trends as those observed for the 2D capture length in Fig. 4 for vapor flux incidence angles larger than $\sim 70^\circ$ and are thus also consistent with the occurrence of a double in-plane alignment.

The findings presented above are to be compared to the Cr film where grains with different out-of-plane orientations are present during the initial film formation. For an [111] out-of-plane oriented crystal with {110} facets the capture length calculation yielded qualitatively similar results to those for the [110] oriented crystal (see Fig. 4), i.e., three maxima at $\omega = 0^\circ$, 90° , and 180° ($\omega = 0^\circ$ and 180° correspond to the same in-plane alignment due to symmetry) with the one at $\omega = 90^\circ$ being less favored ($\sim 60\%$ of the value for $\omega = 0^\circ$).²⁶ Compared to the in-plane alignment extracted from the pole figures of the Cr film grown directly on the Si substrate with an [111] out-of-plane orientation (see Fig. 3), only the in-plane alignment that corresponds to the longest capture length is observed. This is consistent with the commonly accepted notion that islands with other in-plane alignments are overgrown.⁹ Since the latter is not the case for the Cr/Ti film where only in-plane competition is present, we suggest that the existence of grains with an out-of-plane orientation different than the dominant one during island growth and impingement changes the shadowing conditions and adatom/vapor capture conditions, affecting the resulting in-plane alignment. This in turn may explain the discrepancy between the in-plane selection model by Mahieu *et al.*⁹ and experimental results on in-plane orientation of biaxially textured films.

In summary, we compiled and implemented an experimental strategy that provides growth conditions consistent with the key assumptions of the in-plane orientation selection model for biaxially textured films proposed by Mahieu *et al.*⁹ The model predicts in-plane alignment by considering

faceted grains that all exhibit the same out-of-plane orientation overlooking the fact that in vapor condensation experiments out-of-plane orientation first is determined during the competitive growth process. Here, we grow a Cr film off-normally onto a fiber textured Ti (0002) epilayer in order to preset a Cr (110) out-of-plane orientation while still maintaining a random in-plane alignment. Our results reveal a biaxially textured Cr (110) film that possesses a double in-plane alignment, which is demonstrated to be consistent with the predicted in-plane alignments from capture length calculations in the model. The experimental strategy presented herein can be used to gain insight on the atomistic mechanisms that determine in-plane orientation selection, which, in turn, is relevant for improving modeling approaches and tuning microstructure of biaxially textured thin films in a knowledge based manner.

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- ¹D. Dimos, P. Chaudhari, J. Mannhart, and F. K. LeGoues, *Phys. Rev. Lett.* **61**, 219 (1988).
- ²S. R. Foltyn, P. N. Arendt, Q. X. Jia, H. Wang, J. L. MacManus-Driscoll, S. Kreiskott, R. F. DePaula, L. Stan, J. R. Groves, and P. C. Dowden, *Appl. Phys. Lett.* **82**, 4519 (2003).
- ³Y. Xu, C. H. Lei, B. Ma, H. Evans, H. Efsthadiadis, R. Manisha, M. Massey, U. Balachandran, and R. Bhattacharya, *Supercond. Sci. Technol.* **19**, 835 (2006).
- ⁴A. T. Findikoglu, W. Choi, V. Matias, T. G. Holesinger, Q. X. Jia, and D. E. Peterson, *Adv. Mater.* **17**, 1527 (2005).
- ⁵C. Gaire, P. C. Clemmer, H.-F. Li, T. C. Parker, P. Snow, I. Bhat, S. Lee, G.-C. Wang, and T.-M. Lu, *J. Cryst. Growth* **312**, 607 (2010).
- ⁶H. Li, P. Snow, M. He, P.-I. Wang, G.-C. Wang, and T.-M. Lu, *ACS Nano* **4**, 5627 (2010).
- ⁷M. Ohring, *Materials Science of Thin Films*, 2nd ed. (Academic Press, San Diego, 2002).
- ⁸C. V. Thompson and R. Carel, *Mater. Sci. Eng., B* **32**, 211 (1995).
- ⁹S. Mahieu, P. Ghekiere, D. Depla, and R. De Gryse, *Thin Solid Films* **515**, 1229 (2006).
- ¹⁰G. H. Gilmer, H. Huang, T. Díaz de la Rubia, T. Dalla Torre, and F. Baumann, *Thin Solid Films* **365**, 189 (2000).
- ¹¹F. H. Baumann, D. L. Chopp, T. Díaz de la Rubia, G. H. Gilmer, J. E. Greene, H. Huang, S. Kodambaka, P. O'Sullivan, and I. Petrov, *MRS Bull.* **26**, 182 (2001).
- ¹²L. Abelman and C. Lodder, *Thin Solid Films* **305**, 1 (1997).
- ¹³X. W. Zhou and H. N. G. Wadley, *Surf. Sci.* **431**, 42 (1999).
- ¹⁴K. Hasegawa, N. Hobara, Y. Nakamura, T. Izumi, and Y. Shiohara, *Phys. C* **354**, 424 (2001).
- ¹⁵O. P. Karpenko, J. C. Bilello, and S. M. Yalisove, *J. Appl. Phys.* **76**, 4610 (1994).
- ¹⁶S. Mahieu, P. Ghekiere, D. Depla, R. De Gryse, O. I. Lebedev, and G. Van Tendeloo, *J. Cryst. Growth* **290**, 272 (2006).
- ¹⁷S. Mahieu, “Biaxial alignment in sputter deposited thin films,” Ph.D. thesis (Ghent University, 2006).
- ¹⁸P. Ghekiere, “Structure evolution of biaxially aligned thin films deposited by sputtering,” Ph.D. thesis (Ghent University, 2007).
- ¹⁹M. Saraiva and D. Depla, *J. Appl. Phys.* **111**, 104903 (2012).
- ²⁰P. Ghekiere, S. Mahieu, R. De Gryse, and D. Depla, *Thin Solid Films* **515**, 485 (2006).
- ²¹P. Ghekiere, S. Mahieu, G. De Winter, R. De Gryse, and D. Depla, *Thin Solid Films* **493**, 129 (2005).
- ²²R. Deng, P. Muralt, and D. Gall, *J. Vac. Sci. Technol., A* **30**, 051501 (2012).
- ²³V. Elofsson, D. Magnfält, M. Samuelsson, and K. Sarakinos, *J. Appl. Phys.* **113**, 174906 (2013).
- ²⁴K.-H. Müller, *J. Appl. Phys.* **58**, 2573 (1985).
- ²⁵I. Petrov, P. B. Barna, L. Hultman, and J. E. Greene, *J. Vac. Sci. Technol., A* **21**, S117 (2003).

- ²⁶See supplementary material at <http://dx.doi.org/10.1063/1.4903932> for Cr/Ti epitaxial relationship, Ti texture, assisting Cr pole figures, crystal orientation, and capture cross section calculations.
- ²⁷J. Narayan and B. C. Larson, *J. Appl. Phys.* **93**, 278 (2003).

- ²⁸R. A. Schwarzer, *Textures Microstruct.* **20**, 7 (1993).
- ²⁹G. Greczynski, J. Jensen, and L. Hultman, *Thin Solid Films* **519**, 6354 (2011).
- ³⁰L. Chen, T.-M. Lu, and G.-C. Wang, *J. Appl. Phys.* **112**, 024303 (2012).