Superior Regularity in Erosion Patterns by Planar Subsurface Channeling

Alex Redinger,[1] Henri Hansen,[1] Udo Linke,[2] Yudi Rosandi,[3] Herbert M. Urbassek,[3] and Thomas Michely[1,*]

[1]*I. Physikalisches Institut, RWTH Aachen, 52056 Aachen, Germany*

[2]*Institute of Thin Films and Interfaces, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*

[3]*Fachbereich Physik, Universität Kaiserslautern, Erwin-Schrödinger-Straße, 67663 Kaiserslautern, Germany*

(Received 9 November 2005; published 16 March 2006)

The onset of pattern formation through exposure of Pt(111) with 5 keV Ar^+ ions at grazing incidence has been studied at 550 K by scanning tunneling microscopy and is supplemented by molecular-dynamics simulations of single ion impacts. A consistent description of pattern formation in terms of atomic scale mechanisms is given. Most surprisingly, pattern formation depends crucially on the angle of incidence of the ions. As soon as this angle allows subsurface channeling of the ions, pattern regularity and alignment with respect to the ion beam greatly improves. These effects are traced back to the positionally aligned formation of vacancy islands through the damage created by the ions at dechanneling locations.

DOI: 10.1103/PhysRevLett.96.106103 PACS numbers: 81.16.Rf, 61.80.Jh, 79.20.Ap, 79.20.Rf

By grazing incidence ion scattering from metal surfaces a wealth of information and a deep understanding of many aspects of the ion-surface interaction has been obtained. Charge exchange between surface and projectile, electronic energy loss of the projectile, as well as electron emission due to scattering were extensively investigated (for a current review see [1]). The grazing incidence scattering geometry also played an important role in uncovering the interaction of highly charged ions with surfaces [2–4]. Despite this impressive knowledge gathered primarily through the analysis and spectroscopy of the scattered particles, very little is known about the damage left behind on the surface as a consequence of the collision. This is more surprising, as this damage is relevant whenever the scattered ions are used as a measuring tool for surface processes or structure (e.g., [5]). It is even crucial in applications of grazing ion beams like ion beam smoothening [6], thin film growth manipulation [7], nanopattern formation [8,9], or ion beam milling [10].

One step towards an interpretation of morphologies resulting from grazing incidence ion bombardment is the distinction between terrace damage and step edge damage [11]. Here we show for the first time how a specific damage mechanism at step edges acting only under grazing incidence conditions couples into the formation of mesoscopic damage structures. The alignment and overall periodicity of erosion patterns improve dramatically if the ion beam is tuned to conditions where planar subsurface channeling takes place. Planar subsurface channeling is the guided motion of ions between lattice planes parallel to the surface. It was discovered in ion-surface scattering experiments by characteristic energy losses of the scattered particles [12].

The experiments were performed in an ultrahigh vacuum variable temperature scanning tunneling microscopy (STM) apparatus with a base pressure in the 10^{-11} mbar range. Sample cleaning was accomplished by flash annealing to 1273 K and sputtering by a mass separated ion beam. For the grazing incidence experiments the clean surface was exposed to fluxes in the range of $1.8\text{–}2.8 \times 10^{16}$ ions $m^{-2}\,s^{-1}$ of 5 keV Ar^+ incident along the $[\bar{1}\,\bar{1}\,2]$ and the $[\bar{1}10]$ direction at angles $\vartheta \in [78°, 89°]$ to the surface normal at various exposure times and temperatures. In the following the ion fluence F (the product of ion flux and exposure time) is specified in monolayer equivalents (MLE), where 1 MLE $= 1.504 \times 10^{19}$ ions/m^2. Here we focus on the onset of pattern formation ($F \leq 2$ MLE, ion beam in the $[\bar{1}\,\bar{1}\,2]$ direction) between 350 and 550 K.

In order to elucidate the atomistic details of the processes occurring under ion impact, we performed molecular-dynamics (MD) simulations of these events. Simulations were performed for a target crystallite both at 0 and at 550 K. While the simulations at 0 K are standard [13], we note that for the high-temperature simulations it was essential to fix the bottommost layer of the crystallite in order to stabilize it against ‘‘floppy’’ long-wavelength vibrational and torsional modes.

Figure 1 compares STM topographs after ion bombardment with $\vartheta = 79°$ [Figs. 1(a)–1(c)] and $\vartheta = 83°$ [Figs. 1(d)–1(f)] at 550 K. The ion fluences increase from top to bottom and were chosen such that the eroded amounts for the two sequences are comparable. The direction of the ion beam is indicated in Fig. 1(a) by a white arrow. We first consider the case of $\vartheta = 79°$. After 0.25 MLE in Fig. 1(a) a large number of compact vacancy islands of monolayer depth with step edges aligned along the dense packed $\langle 110 \rangle$ directions are present. Also few small adatom islands are visible. According to our MD simulations at $\vartheta = 79°$ ion impacts on a perfect terrace cause only small sputtering and adatom production (terrace sputtering yield $Y_S^{terr} \approx 0.44$ and terrace adatom yield $Y_A^{terr} \approx 2.7$), while impacts hitting an ascending step edge either directly or after reflection from the terrace cause significant sputtering (step edge sputtering yield $Y_S^{step} \approx 9.9$ and adatom yield $Y_A^{step} \approx 28$). Neglecting preexisting steps, initially only terrace impacts take place. Only few surface vacancies are formed which agglomerate to va-

