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## Electric forces on a confined *advacancy* island

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The passage of an electric current in a material can cause a biased mass transport at its surface. This migration phenomenon is intimately related to the microscopic details of atomic processes of diffusion and attachment/detachment at step edges. Using low energy electron microscopy we have examined *in operando* under an electric current the migration of Si(111)-1×1 *advacancy* islands confined on Si(111)-7×7 terraces. The islands move opposite to the current direction, with velocity increasing with the radius. The effective valence of Si *adatoms* is  $2.8\pm 0.5$  and the kinetic length of attachment-detachment is about 500 nm. The analysis of the islands shape reveals that the electric current biases significantly the kinetic rate of mass transfers at step edges modifying the overall island shape.

Advances in the fabrication of nanostructures widely depend on the degree of knowledge of atomic processes at surfaces. In that respect atomic steps, as the most abundant structures at surfaces, play a key role in mass transfers. They are involved in complex atomic mechanisms such as the attachment-detachment of atoms or the atomic diffusion at the periphery of nanostructures [1 and 2]. To study the mass transfer mechanisms, different experimental strategies have been carried out based on the spatio-temporal fluctuations of the position of isolated/interacting steps [3–5] or on the step displacement velocity when a driving force intervenes using the fluctuation-dissipation theorem [6–8]. In particular the application of an electric current is known to bias the diffusion of mobile *adatoms*. This effect, called electromigration [9–15], can cause substantial changes in the surface morphology such as step bunching for vicinal surfaces [16–19] or shape instabilities of 2D islands [20–24]. However it has been recently recognized that an electric current may not only impact *adatom* diffusion but also atomic steps themselves by modifying their local properties such as the *adatom* equilibrium concentration close to the step and/or the kinetic coefficients of attachment-detachment at step edges [5, 25, and 26]. These effects arise since the force acting on atoms depends on their local environment that differs at step edge, kink site or on top of a terrace. These local modifications of step properties are, to date, largely unknown whereas they are suspected to be extremely strong [5 and 25]. Moreover a better understanding of the effects of the electric current on surface mass transport gives also indirect information about the electric resistance of surfaces [27]. Indeed the electric forces acting on atoms, kink sites and step edges are compensated by opposite forces acting on charge carriers caused by these surface structures. These forces change the surface electric resistivity and may play a major role in electrical conductors when down-scaling in size [28 and 29]. This calls for specific studies on the effect of an electric current on the step properties and mass transport phenomena at the nanoscale.

In this letter we analyze quantitatively the atomic mechanisms of mass transport and step properties on

Si(111) under an electric bias by addressing precisely the boundary conditions to disentangle all the contributions. In that purpose we have met two essential conditions: (1) An *advacancy* island where atomic displacements occur at the interior of a confined 2D space closed by a step edge; and (2) a driving force induced by an electric current to move the island. By adjusting the area of the island and measuring its drift velocity induced by an electric current we determine the mechanisms of mass transfers. This study is based on an *in operando* observation under an electric current of the Si(111) surface with low energy electron microscopy (LEEM). The experimental set-up allows to study the spatio-temporal dynamics of mass transfers at atomic steps [30]. We show a transition from a kinetics of mass transfer limited by attachment-detachment of atoms at step edges for small islands to a kinetics limited by terrace diffusion for large islands. We deduce that the kinetic length for attachment/detachment is  $d \sim 500$  nm and the effective valence  $Z^*$  of the Si *adatoms* at the surface is  $2.8\pm 0.5$ . Importantly our detailed analysis of the stationary shape of the electromigrating *advacancy* islands is consistent with a strong modification of the local properties of attachment/detachment at step edges induced by the electric current.

The experiments were performed in an ultra high vacuum (UHV) setup equipped with a low energy electron microscope (LEEM III, Elmitec GmbH) [30]. Si(111) substrates (n or p-doped,  $\rho=1 \Omega\text{cm}$ ) were cut into pieces of  $15\times 3\times 0.5 \text{ mm}^3$ , cleaned with acetone and ethanol before introduction in UHV. An electric current is applied through the sample *via* two Mo electrodes clamped to its extremities. The samples were degassed in UHV for several hours at about 1100 K and then flashed above 1500 K for a few seconds by direct current heating. *Advacancy* islands are created by Si sublimation in the middle of large terraces [31]. The surface evolution under electromigration is studied by LEEM in bright field mode, with an electron beam energy of 3 eV. To change the *advacancy* islands size, Si was deposited *in situ* by a homemade direct current evaporator made of a piece of Si wafer clamped between Mo electrodes.

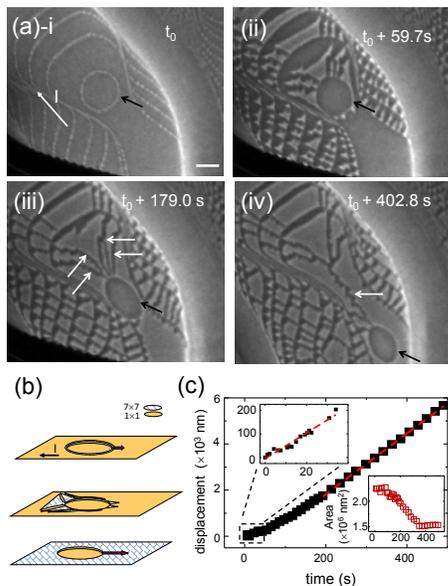


FIG. 1. (a) Sequence of LEEM images during the  $1\times 1 \rightarrow 7\times 7$  phase transition and under electric heating (see complete movie S1 in the supplementary materials). (i) Nucleation of  $7\times 7$  surface reconstruction at the step edges on the upper terraces. (ii) Spreading of the  $7\times 7$  onto the terraces except in the *advacancy* island (black arrow) where the  $7\times 7$  nucleation is hindered. (iii) Formation of  $1\times 1$  out-of-phase boundaries at the  $7\times 7$  domain intersections (white arrows). (iv) Migration of the *advacancy* island in the  $\langle 1\bar{1}2 \rangle$  direction, opposite to the electric current. Out-of-phase boundaries merging at the rear side of the island. Electron energy  $E=3$  eV. Scale bar  $1\mu\text{m}$ . (b) Scheme of the surface evolution under slow cooling. (c) Time evolution of the displacement of the *advacancy* island (black square). The steady velocity is  $13.1\pm 0.1$  nm.s<sup>-1</sup> (velocity in (a)-i is  $5.4\pm 0.3$  nm.s<sup>-1</sup>, see top inset) and the area is  $1.5\pm 0.1$   $10^6$  nm<sup>2</sup> (see bottom inset).

LEEM images in Fig. 1(a) show the time evolution of the Si(111) surface while crossing the  $1\times 1 \rightarrow 7\times 7$  phase transition temperature (1133 K). The low temperature  $7\times 7$  surface reconstruction nucleates at the step edges on the upper terraces [32] and appears as bright lines (Fig. 1(a)-i). Upon slow cooling, by decreasing the electric current, the  $7\times 7$  phase extends onto the terraces (Fig. 1(a)-ii). Since the crystallographic arrangement of the different  $7\times 7$  domains does not necessarily coincide,  $1\times 1$  out-of-phase boundaries persist at their intersections. Moreover the nucleation of the  $7\times 7$  phase is hindered at the lower step edges and on terraces [7], therefore the *advacancy* island in the middle of Fig. 1(a)-iii stays in a metastable supercooled  $1\times 1$  state [33]. This effect was originally described as a hysteresis of the  $1\times 1 \leftrightarrow 7\times 7$  phase transition temperature [34]. Interestingly this *advacancy* island migrates in the direction opposite to the electric current (Fig. 1(a)-iii-iv). During the displacement, the out-of-phase boundaries attached at the rear of the island merge from time to time and/or spontaneously detach. The velocity of the *advacancy* island

increases up to  $13.1\pm 0.1$  nm.s<sup>-1</sup> and reaches a stationary value when the  $7\times 7$  phase significantly covers the surrounding surface. Simultaneously, after an initial size reduction due to mass transfers with the exterior, the island size reaches also a steady state. Mass transfers have two contributions: The Gibbs-Thompson effect favors the capture of *adatoms* as the *advacancy* island curvature is locally the largest one (in absolute). The phase transition expels the excess atoms of the  $1\times 1$  that diffuse to the step edge [35]. The fact that the island area stabilizes indicates that mass transfers from the exterior are nearly entirely suppressed when the  $7\times 7$  covers most of the surface. This diffusion barrier effect [36] is due to the large surface diffusivity of Si *adatoms* on the  $1\times 1$  with respect to the  $7\times 7$  (ratio $\sim 20$ , [7]). During its displacement the *advacancy* island can reach a step edge or a defect that may induce the nucleation of the  $7\times 7$  inside the island. To prevent this process from occurring the electric current direction is regularly reversed to change the drift direction by electromigration while keeping a constant temperature ( $\pm 1$  K). The islands move back and forth over a distance larger than  $10\mu\text{m}$  on extended terraces without meeting any surface defect or step (Fig. 2(b)). Concomitantly this process allows for the disappearance of all  $1\times 1$  out-of-phase boundaries attached to the islands by merging and detachment from the rear side and by removal at the front side. Let us note that a few out-of-phase boundaries have barely no effect on the measured velocity but their removal is important to determine the stationary shape of the *advacancy* island without ambiguity.

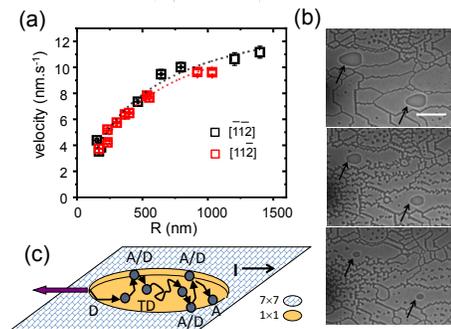


FIG. 2. (a) *Advacancy* island velocity versus radius. The islands electromigrate in the  $\langle 1\bar{1}2 \rangle$  (black square) and  $\langle 11\bar{2} \rangle$  (red square) directions. Fit of the velocity (dotted lines). (b) LEEM images of islands of different sizes electromigrating in the  $\langle 11\bar{2} \rangle$  direction (scale bar  $5\mu\text{m}$ , see complete movie S2 in the supplementary materials). (c) Scheme of mass transfer process: detachment of atoms (D), biased terrace diffusion (TD) and attachment (A).

To address the mass transport mechanisms that are occurring inside the *advacancy* islands under electromigration we have studied the size-dependence of the island velocity in the stationary regime. Figure 2(a) shows that the velocity increases with the island effective radius  $R$  ( $R = \sqrt{A/\pi}$  where  $A$  is the island area). Pierre-Louis *et*

150 *al.* [20] have analyzed the island velocity in the frame-  
 151 work of the linear response theory with weak electromi-  
 152 gration. Considering a kinetics of mass transport by at-  
 153 tachment (A), detachment (D) and terrace diffusion (TD)  
 154 inside the  $1 \times 1$  *advacancy* island (see Fig. 2(c)), and ne-  
 155 glecting the *adatom* flux from the upper terrace ( $7 \times 7$ ),  
 156 the island drift velocity resulting from these processes is  
 157 [20]:

$$V_{isl} = c_{eq} v_{1 \times 1} \frac{R}{R + d} \quad (1)$$

158 where  $c_{eq}$  is the equilibrium surface concentration of mobile  
 159 *adatoms*,  $v_{1 \times 1}$  is the *adatoms* velocity on the  $(1 \times 1)$   
 160 terrace and  $d = D_{1 \times 1}/k$  is the kinetic length of attach-  
 161 ment/detachment and is defined as the ratio of the sur-  
 162 face diffusion coefficient  $D_{1 \times 1}$  to the rate  $k$  of *adatom*  
 163 attachment to the step from the terrace. Let us note that  
 164 the mechanism of periphery diffusion of atoms along the  
 165 step edge has been neglected since the velocity should  
 166 decay as  $1/R$  [20] and no evidence of this behavior is  
 167 measured even for the smallest radius. The fit of the ex-  
 168 perimental plots give two key parameters  $c_{eq} v_{1 \times 1}$  and  $d$ .  
 169 The first term is deduced from the asymptotic velocity at  
 170 large radius ( $15 \pm 1$  nm.s $^{-1}$ ) and is only related to terrace  
 171 diffusion of the electromigrating *adatoms*. To estimate  
 172 the *adatom* velocity  $v_{1 \times 1}$  we have to determine first  $c_{eq}$ .  
 173 Since the step edge is hybrid,  $1 \times 1$  reconstructed on the  
 174 lower terrace and  $7 \times 7$  on the upper one, the equilib-  
 175 rium concentration of *adatom* close to the step edge is  
 176 unknown. We have measured the *adatom* concentration  
 177 in the  $1 \times 1$  *advacancy* island by decreasing the temper-  
 178 ature to induce the  $1 \times 1 \rightarrow 7 \times 7$  phase transition. The  
 179 excess of *adatoms* expelled by the phase transition con-  
 180 densates at step edges and shrinks the *advacancy* island  
 181 area (see supplementary materials S3). The area fraction  
 182 lost after the phase transition is  $0.08 \pm 0.02$ . Moreover  
 183 considering that the  $7 \times 7$  and the bulk-terminated  $1 \times 1$   
 184 structure have a difference of atomic density of 0.04 [35],  
 185 we can estimate that the density of mobile *adatoms* of  
 186 the  $1 \times 1$  is  $0.12 \pm 0.02$ . As the steps on Si(111) are bi-  
 187 layers this corresponds to  $0.24 \pm 0.04$  monolayer (ML)  
 188 of *adatoms* on the  $1 \times 1$  surface of the *advacancy* is-  
 189 land. This result is similar to 0.2 ML as estimated by  
 190 [35] considering the  $1 \times 1$  surface. This result is also  
 191 consistent with the fact that the equilibrium concentra-  
 192 tion of *adatoms* is a thermodynamic quantity. It is re-  
 193 lated to a difference of energy between two states: an  
 194 atom attached at a step edge and on a terrace (*adatom*).  
 195 As the chemical environments of an atom attached to a  
 196  $7 \times 7$  or  $1 \times 1$  step edge are similar and very distinct  
 197 from an *adatom* on top of a  $1 \times 1$  terrace, we expect  
 198 that the step edge reconstruction only slightly modifies  
 199 the equilibrium concentration. Using our experimental  
 200 result of  $c_{eq}$  and correcting the velocity with *advection*  
 201 [37] (sweeping effect on the *adatoms* due to the step mo-  
 202 tion) we get finally the *adatom* velocity  $v_{1 \times 1} = 110 \pm 8$   
 203 nm.s $^{-1}$  on the  $1 \times 1$  surface reconstruction at the phase  
 204 transition temperature. This velocity derives from the

205 Einstein relation  $v_{1 \times 1} = \frac{D_{1 \times 1}}{k_B T} F$  where  $k_B$  is the Boltz-  
 206 mann constant,  $T$  the temperature and  $F = Z^* e E$  the  
 207 electromigration force. Therefore the force and the ef-  
 208 fective charge  $Z^*$  of Si *adatoms* can be obtained if the  
 209 diffusion coefficient  $D_{1 \times 1}$  is known. Hibino *et al.* have  
 210 found  $D_{1 \times 1} c_{eq} = 3.0 \cdot 10^7$  s $^{-1}$  [7 and 33] at the phase  
 211 transition temperature. Pang *et al.* have obtained by  
 212 different approaches  $D_{1 \times 1} c_{eq} = 2.0 \pm 0.2 \cdot 10^7$  s $^{-1}$  [8] in a  
 213 slightly higher temperature regime (1163 K). Considering  
 214 an average value for  $D_{1 \times 1}$  we can deduce  $F = 1.4 \pm 0.3$   
 215  $10^{-6}$  eV.nm $^{-1}$  and the only free parameter, *i.e.* the ef-  
 216 fective charge of Si *adatoms*  $Z^* = 2.8 \pm 0.5$  ( $E = 490$   
 217 V.m $^{-1}$ , atomic area: 0.064 nm $^2$ ). The deduced value of  
 218  $Z^*$  is larger by one order of magnitude with earlier re-  
 219 ports [38 and 39] except for [40] ( $Z^* > 1.3$ ). The model  
 220 hypothesis of a weak electromigration is confirmed since  
 221 the available thermal energy is much larger than the en-  
 222 ergy to electromigrate  $\frac{F a}{k_B T} \sim 10^{-5} \ll 1$  where  $a = 0.384$   
 223 nm is the atomic lattice parameter [20]. The second term  
 224 that is deduced from the fit is the kinetic length of at-  
 225 tachment/detachment  $d$ . We obtain  $d_{\langle 11\bar{2} \rangle} = 450 \pm 100$   
 226 nm and  $d_{\langle \bar{1}12 \rangle} = 500 \pm 30$  nm respectively for an island  
 227 displacement in the  $\langle 11\bar{2} \rangle$  and the  $\langle \bar{1}12 \rangle$  directions. It  
 228 is interesting to note that, contrary to the equilibrium  
 229 concentration that is close to the  $1 \times 1$  surface, the kinetic  
 230 length of attachment/detachment at the hybrid step edge  
 231 is similar to the one measured at the step edges of the  
 232  $7 \times 7$  reconstructed surface [41]. To explain this kinetic  
 233 length we can note that, as for the  $7 \times 7$  reconstructed  
 234 surface, the advance of the hybrid step edge needs also  
 235 to build  $7 \times 7$  unit cells. This process is related to en-  
 236 ergy barriers and probably to the occurrence of concerted  
 237 events that are necessary to achieve the complex mech-  
 238 anisms involved in the formation of a  $7 \times 7$  unit cell [42  
 239 and 43]. From the evaluation of  $d$  we can estimate the  
 240 rate of attachment/detachment at a step edge per atomic  
 241 site  $k c_{eq} a = c_{eq} D_{1 \times 1} a / d \sim 1.9 \times 10^4$  s $^{-1}$ . It is also in-  
 242 structive to estimate the average macroscopic time for  
 243 *adatoms* to detach from the front side, cross the island  
 244 and attach at the rear side. The traveling time across  
 245 the terrace by diffusion is about  $t_d \sim 2R/v_{1 \times 1}$  and for a  
 246 typical island of 1  $\mu$ m radius  $t_d \sim 15$  s. As a comparative  
 247 time scale, the delay time for an atom to make all attach-  
 248 ment/detachment processes to cross the island is about  
 249  $t_{AD} \sim 2d/v_{1 \times 1} \sim 6$  to 8 s. This indicates that many  
 250 events of (re)-attachment-detachment occur during this  
 251 traveling ( $k c_{eq} a \times t_{AD} \sim 10^5$ , see Fig.2(c)).

253 In addition to velocity, the *advacancy* island shape in  
 254 the stationary regime is measured and depends both on  
 255 the island size and electric current direction. In Fig. 3(a),  
 256 the *advacancy* islands have a faceted front and an overall  
 257 triangular shape when they migrate in the  $\langle 11\bar{2} \rangle$  direction  
 258 whereas they have a lozenge shape (elongated head and  
 259 lateral facets) in the opposite direction. If they move  
 260 in the  $\langle \bar{1}10 \rangle$  direction the shape is no more symmetric  
 261 (Fig. 3(d)). In all cases the shape is elongated in the  
 262 migration direction. This elongation increases with the  
 263 island size and tends to be circular for small sizes (the

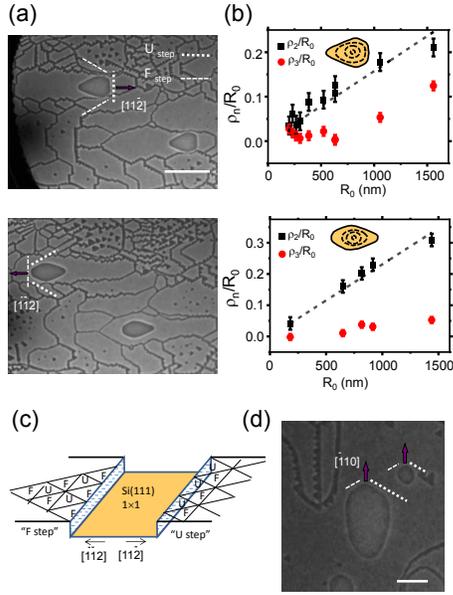


FIG. 3. (a) LEEM images of *advacancy* islands electromigrating in the  $\langle 11\bar{2} \rangle$  (top) and the  $\langle \bar{1}\bar{1}2 \rangle$  (bottom) directions (scale bar  $5 \mu\text{m}$ ). The shape is respectively a triangle and a lozenge. Unfaulted steps ( $U_{step}$ ) are shown as dotted lines and faulted steps ( $F_{step}$ ) as dashed lines [44]. (b) Fourier coefficients of the island shape as function of island radius for both direction. (c) Scheme of the  $U$  and  $F$  step edge structure. (d) LEEM image of two *advacancy* islands electromigrating in the  $\langle 1\bar{1}0 \rangle$  direction. The shape is asymmetric (scale bar  $1 \mu\text{m}$ , see complete movie S4 in the supplementary materials).

264 typical crossover is about the attachment-detachment ki-  
 265 netic length  $d$ ). To describe the island shape, we use the  
 266 polar coordinates  $R(\theta) = R_0 + \rho(\theta)$  ( $R_0$  is the mean ra-  
 267 dius), and we apply the Fourier series expansion of  $\rho(\theta)$ :

$$\rho(\theta) = \sum_{n \geq 2}^{\infty} \rho_n \cos(n\theta) + \nu_n \sin(n\theta) \quad (2)$$

268 where  $\rho_n$  and  $\nu_n$  are the Fourier coefficients ( $\nu_n = 0$  for  
 269 symmetric islands and  $\rho_1$  and  $\nu_1$  are not considered be-  
 270 cause they correspond to a simple shape translation). In  
 271 Fig. 3(b) are plotted the normalized Fourier coefficients  
 272  $\rho_n/R_0$  as function of the island radius  $R_0$  when the is-  
 273 lands are migrating along the  $\langle 11\bar{2} \rangle$  and  $\langle \bar{1}\bar{1}2 \rangle$  directions.  
 274 The main term of elongation is the  $n=2$  mode  $\rho_2/R_0$   
 275 and in both cases it increases approximately linearly with  
 276 the island radius.  $\rho_2/R_0$  is larger when the island has a  
 277 lozenge shape. The triangular shape of the islands mi-  
 278 grating in the  $\langle 11\bar{2} \rangle$  direction is given by a strong  $n=3$   
 279 mode  $\rho_3/R_0$  that is increasing non-linearly with the is-  
 280 land radius.

281 Our first insight into the island shape and symmetry  
 282 is based on crystallographic considerations. The step  
 283 edge properties of the  $7 \times 7$  have a threefold symmetry  
 284 [45 and 46]. However due to symmetry breaking by elec-  
 285 tromigration, maximum a mirror symmetry can be ex-

286 pected. As observed experimentally if the electric cur-  
 287 rent is along the symmetry axis  $\langle 11\bar{2} \rangle$  the shape has a  
 288 mirror line whereas it is not the case when the electric  
 289 current is along the non-symmetric  $\langle \bar{1}\bar{1}0 \rangle$  direction (Fig.  
 290 3(d)). As the shape is far from equilibrium the kinetic  
 291 of mass transfers such as the one involved in the attach-  
 292 ment/detachment of atoms at step edges is expected to  
 293 play a major role.

294 In the framework of a continuous step model with  
 295 isotropic surface properties, the shape of *advacancy* is-  
 296 lands driven by an electromigration force on *adatoms* and  
 297 considering mass transfers by terrace diffusion and at-  
 298 tachment/detachment at step edges has been calculated  
 299 [20, 24, and 37]. The elongation of the *advacancy* islands  
 300 is perpendicular to the migration direction. This shape  
 301 can be qualitatively interpreted as resulting from a mass  
 302 flux towards the migration axis. Indeed in presence of  
 303 a slow kinetics of attachment, the *adatoms* make several  
 304 trials before attaching to the step and have a residual  
 305 drift towards the migration axis. In a steady state the  
 306 local curvature of the island is modified to compensate  
 307 this mass flux by a capillary effect. Quantitatively the  
 308 change of shape involves the  $n = 2$  mode as  $\rho_2/R_0$  ratio  
 309 (elongation) and reads ([20] for  $d \ll R_0$ ):

$$\frac{\rho_2}{R_0} = -\frac{1}{12\Gamma} \frac{R_0^2}{\xi^2} d < 0 \quad (3)$$

310 where  $\Gamma = \frac{a^2 \tilde{\beta}}{k_B T}$  is the capillary length (Gibbs-Thomson  
 311 effect),  $\tilde{\beta}$  is the step edge stiffness and  $\xi$  is a charac-  
 312 teristic length associated with the electromigration force  
 313 ( $\xi = \frac{k_B T}{F} = 70 \mu\text{m}$ ). This result is opposite to the ex-  
 314 perimental shape since the elongation of the *advacancy*  
 315 islands is along the migration direction ( $\frac{\rho_2}{R_0} > 0$ ). As this  
 316 result is observed whatever the direction of the electric  
 317 current we infer that even if the modeling could include  
 318 the anisotropy of the surface properties, it alone could  
 319 not explain that the shape is always elongated along the  
 320 migration axis. Therefore we propose that the electric  
 321 current modifies not only the *adatom* displacement but  
 322 also the atomic step properties. As a minimum model,  
 323 the electric current breaks the threefold symmetry of the  
 324 kinetic rate of attachment-detachment at the step edges  
 325 [47]. To study this effect we expand the kinetic length  $d$   
 326 as a Fourier series  $d = \bar{d} + \sum_n d_n \cos(n\theta)$  where  $\bar{d}$  is the  
 327 mean kinetic length of attachment/detachment and  $d_n$   
 328 are the Fourier coefficients for a symmetric shape. The  
 329 main Fourier term acting as an electrobias, *i.e.* chang-  
 330 ing the kinetics of attachment-detachment at the step  
 331 edge, is expected to be  $d_1$  since it breaks the symmetry  
 332 between the island front where the current is step-down  
 333 and the island rear where the current is step-up. Let  
 334 us note that without electrobias only  $d_{3n}$  exists by sym-  
 335 metry. Expanding linearly the shape of the *advacancy*  
 336 island with this electrobias effect we obtain:

$$\frac{\rho_2}{R_0} = -\frac{1}{12\Gamma} \left[ \frac{R_0^2}{\xi^2} \left( \bar{d} + \frac{d_2}{2} \right) - 2 \frac{R_0}{\xi} (d_1 + d_3) \right] \quad (4)$$

337 The shape elongation  $\frac{\rho_2}{R_0}$  shows a new contribution that  
 338 increases linearly with the island radius  $R_0$  as in the mea-  
 339 surements, and is along the migration axis if  $d_1 + d_3 > 0$ .  
 340 As  $\frac{R_0}{\xi} \sim 0.014 \ll 1$  we can neglect the second order con-  
 341 tribution in eq. (4). To estimate only the electrobias  
 342 effect  $d_1$  we use the change of the current direction in  
 343 the experiment. Assuming that  $d_3$  is not significantly af-  
 344 fected by the electrobias effect, since it is a three order  
 345 term in the series expansion and do not coincide with  
 346 the symmetry of the electric current, the inversion of  
 347 the current direction changes  $d_3$  by  $-d_3$  [48]. There-  
 348 fore the kinetic length of electrobias  $d_1$  is obtained by  
 349 averaging both shape elongation  $\frac{\rho_2}{R_0}$  in the  $\langle 11\bar{2} \rangle$  and  
 350 the  $\langle \bar{1}12 \rangle$  directions. We estimate that  $d_1 \sim 83 \pm 12$   
 351 nm ( $\Gamma = 1$  nm [8]) and considering that this contribution  
 352 is thermally activated, we extract the activation energy  
 353  $E_1 = k_B T \ln \left( 1 + \frac{d_1}{d} \right) = 1.5 \cdot 10^{-2}$  eV. This electrobias ef-  
 354 fect on the step edge is much larger than on *adatoms*  
 355 ( $E = Fa/2 \sim 2.6 \cdot 10^{-7}$  eV). This result could be related  
 356 to an intrinsic change of step properties induced by the  
 357 current but it may also arise from a change of kink den-  
 358 sity at step edges. Indeed it has been shown [49] that an  
 359 electric current in the  $\langle 11\bar{2} \rangle$  direction along a step and as-  
 360 cending the kinks favors the formation of an atomically  
 361 straight step edge. Therefore considering that the kinet-  
 362 ics of mass transfers at step edges is mediated by kinks  
 363 then the rate of attachment/detachment could be indeed  
 364 strongly modified by the electric current. Such an electro-  
 365 bias effect on step edges or kink sites has been suspected  
 366 to occur on semiconductor surfaces [50]. On metals a

367 similar electrobias effect has also been found. However  
 368 the studies on Ag metal [5 and 25] have addressed a dif-  
 369 ferent regime of mass transport dominated by atomic dif-  
 370 fusion along the island periphery. The electrobias effect  
 371 was studied considering a different methodology based on  
 372 the analysis of step fluctuations and island velocity but  
 373 not on the island shape whereas it is strongly sensitive to  
 374 the local modifications of the step edge properties [20].

375 In conclusion we have shown on Si(111) surface that  
 376 an *advacancy* island in the  $1 \times 1$  high temperature phase  
 377 and surrounded by the  $7 \times 7$  low temperature phase can be  
 378 stabilized. This regime allows keeping the 2D island in a  
 379 confined state in terms of atomic exchanges. Then under  
 380 the influence of an electric current, the island is moving.  
 381 The analysis of the velocity and shape of the island as  
 382 function of its radius show that (i) Si *adatoms* migration  
 383 on the terrace is biased and they have an effective valence  
 384  $Z^*$  of  $2.8 \pm 0.5$  (ii) the kinetic of attachment/detachment  
 385 of atoms at the step edges is very slow and we evaluate  
 386 the kinetic length as  $\sim 500$  nm. (iii) An electrobias effect  
 387 on the kinetics of attachment/detachment at step edges  
 388 elongates the island shape in the direction of the electric  
 389 current. We believe that a complete modeling including  
 390 all the effects of anisotropy, non-linearities and high den-  
 391 sity of *adatoms* would be necessary to describe precisely  
 392 the island shape.

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