# In-phase step wandering on Si(111) vicinal surfaces: Effect of direct current heating tilted from the step-down direction

M. Degawa,* H. Minoda, Y. Tanishiro, and K. Yagi
*Physics Department, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan*
(Received 15 June 2000; published 5 January 2001)

In-phase step wandering (IPSW), a newly found step instability due to step-down dc heating on Si(111) vicinal surfaces [Jpn. J. Appl. Phys. **38**, L308 (1999)], is studied in detail in the case of dc heating not parallel to the step-down direction, including the time evolution of IPSW. The nucleation and growth of IPSW regions and the reorientation of ridges of IPSW from the step-down direction to the current direction, resulting in the asymmetric wandering of individual steps, are observed. The effects of the current component parallel to the step-down direction and perpendicular to it (parallel to the step direction) are discussed. As a special case an effect of dc heating parallel to the step direction is also studied.

DOI: 10.1103/PhysRevB.63.045309 PACS number(s): 68.35.Bs, 68.35.Fx, 68.35.Md, 68.43.Mn

## I. INTRODUCTION

Surface step instabilities on Si surfaces due to the direct current (dc) heating of the specimen is one of the interesting step dynamics on surfaces.[1–15] On Si(111) surfaces, step bunching and debunching were reported, depending on the step-down or step-up current direction and on the temperature.[1,2,4] In the $1\times1$ phase, above the phase-transition temperature of 830 °C between the $7\times7$ and the $1\times1$ phases, four temperature ranges with different dc heating effects on low off-angle vicinal surfaces have been reported. In range I (830 °C–1000 °C) and range III (1180 °C–1300 °C), a step-down current induced step bunching while a step-up current stabilized a regular array of steps. In ranges II (1000 °C–1180 °C) and IV (1300 °C–) a reversed current effect was observed. It was also reported that antibands, which are step bands with an inclination opposite to step bands, are formed by the dc heating effect in ranges I–III after the formation of the step bands.[11,13,16] There have been many theoretic approaches to explain the formation of step bands and antibands.[7–10,14,15,17–19]

Recently we have reported that the above-mentioned dc heating effects are not only for low off-angle surfaces but also for large off-angle surfaces up to 13°–14° by using samples with a cylindrical groove.[20] We also found a type of step instability called the in-phase step wandering (IPSW hereafter), where steps wander in-phase forming ridges and valleys along the step-down direction with wandering periods of a few microns in areas with step-down heating on the surface of a cylindrical groove whose off angle is up to 13°–14°.[20] The IPSW takes place also on the flat surfaces with definite off-angles.[21] The IPSW takes place only in range II when the dc is along the step-down direction. The IPSW of antibands was also observed *in situ* by reflection electron microscopy (REM) in range II.[23] Periods of IPSW were found to depend on the temperature in range II and have the maximum value at 1100 °C (nearly the middle of range II) and smaller values on both sides of the temperature range II.[23] Such a behavior is quite different from the monotonous decrease of the diffusion length of adatoms in this temperature range.[24] These facts indicate that IPSW is due to the dc heating effect and its period is not related to the diffusion length of the adatoms.

Another important finding by our group is that in the three ranges (I,II,III) the drift direction of adatoms due to dc heating is in the current direction (positive effective charges in three temperature ranges).[25] This finding excludes theoretical approaches to the dc heating effects with a reversal of the effective charge or with a negative effective charge.[10] Based upon the fact that adatoms drift along the current direction, the following understanding for ranges I and II seems to be most probable.

(1) In range I observed step bunching by a step-down current heating is due to the step-down drift force on adatoms, which has been discussed repeatedly assuming steps are impermeable (where the adatom cannot move across steps without attachment and detachment at the steps).[7,9,14]

(2) In range II observed step bunching by a step-up current heating is due to the step-up drift force on adatoms, which has recently been discussed assuming permeable steps.[18,26]

Thus, the IPSW that we have found should be understood as a type of step instability under a step-down drift force on adatoms, probably assuming permeable steps. However, theoretical study of step wandering is only for an isolated step under a step-down drift force assuming impermeable steps.[14]

From an experimental point of view the following studies are indispensable. IPSW is formed by step wandering of each step in phase as mentioned above. Important parameters of IPSW are periods and amplitudes of the wandering steps in an IPSW pattern. Thus, studies of their time evolution, and its off-angle dependence are very important.[21] Studies of the initial stage of IPSW are also interesting.[27] These studies will be reported in separate papers.

Another important study that is reported in the present paper is the study on the dependence of IPSW and step bunching on current directions relative to the step-down direction: studies of step instability due to a drift force component parallel to the step direction. This includes the case when the current is parallel to the step direction.[19] Time evolution of the IPSW pattern in such an oblique current case is also an interesting topic. This includes not only the time evolution of the period and amplitude of IPSW but also the time evolution of the direction of the in-phase of step wandering (ridges). Sato and Uwaha[15] have theoretically discussed the effect of the drift force with a component parallel to the step direction for the wandering of an isolated impermeable step. They concluded that the existence of a drift force component parallel to the step direction breaks the inversion symmetry of the diffusion field along the step direction and it transforms a chaotic behavior of step wandering to a nonchaotic one with a uniform phase shift during the overall receding of the step. This was given as a solution of the Benny equation. In the case of the IPSW, the drift force component perpendicular to the step direction induces a stable IPSW and the drift force component parallel to the steps is expected to cause a phase shift between neighboring steps. In the present paper studies by optical microscopes on these problems are given.

## II. EXPERIMENTAL

A Si(111) wafer (B doped, few $\Omega$ cm) which has 5° off miscut toward the $[11\bar{2}]$ direction ($[11\bar{2}]$ steps on the surfaces) was used. Specimens $7\times1\times0.3\,\mathrm{mm}^3$ in size were cut from the wafer in such a way that their longer sides (current direction) were 0°, 60°, 90°, 150°, 180°, −30°, −90°, and −120° from the $[11\bar{2}]$ step-down direction. They were chemically cleaned and flash heat cleaned several times at 1200 °C in an ultrahigh vacuum (UHV) chamber and then annealed with dc parallel to the longer sides of the specimens at 1100 °C for about 24 h. The temperature was monitored by an optical pyrometer with no emissivity corrections. Time evolution of the IPSW was studied for specimens with dc fed in the direction 60° from the step-down direction. The annealing time was changed from 3 to 48 h. The annealed specimens were *ex situ* observed by an optical microscope (Leica LEIZ-DMR) and/or by a cofocal laser microscope (Lasertech 1LM21W). From the latter observations, height differences between the ridges and valleys of the IPSW on the surface can be measured.

## III. RESULTS

### A. Step instability under heating current tilted from the step-down direction

Figure 1 shows optical micrographs of specimens annealed at 1100 °C for 24 h under various dc directions. All micrographs are reproduced so that the step-down direction (the $[11\bar{2}]$ direction) is upward in the figure. Each panel was taken after dc fed with a particular angle from the step-down direction as indicated. In panel 1 the dc is in the step-down direction and ridges due to IPSW are parallel to the dc direction as schematically drawn in Fig. 2(a). As seen in panels 2 and 8 of Fig. 1 when the dc is fed in the directions of 60° and −30° from the step-down direction, the ridges of the IPSW are neither parallel to the step-down direction nor to the dc directions. The step arrangement in panel 2 of Fig. 1 is schematically shown in Fig. 2(b). In Fig. 1, panel 5, the dc is in the step-up direction and step bands (dark contrast), antibands (bright contrast), and the IPSW of antibands indicated by a solid arrow are seen as schematically drawn in Fig. 2(c). As it is seen in panels 4 and 6 of Fig. 1 when the dc is not parallel to the step-up direction, the direction of the ridges of the IPSW of antibands is almost parallel to the dc direction indicated by a white arrow in each image, although the bunching direction of step bands (dark contrast) and antibands (bright contrast) are perpendicular to the step-up di-

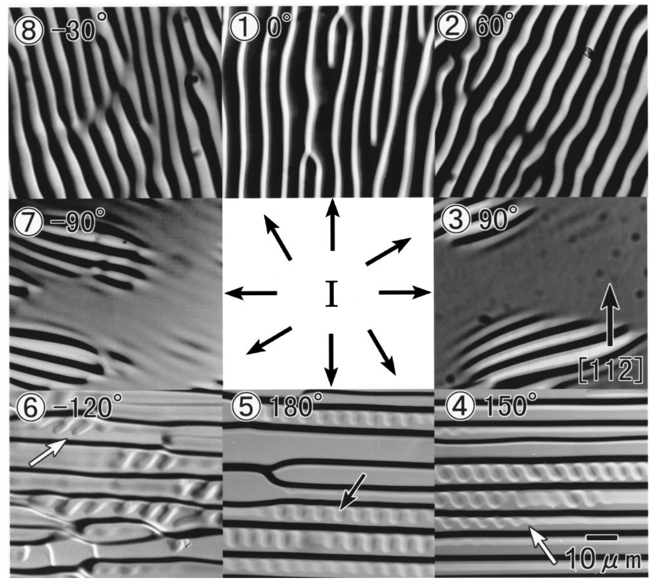


FIG. 1. Optical micrographs of specimens annealed at 1100 °C for 24 h with the dc fed along various directions. Current directions are for panel 1, 0°, for panel 2, 60°, for panel 3, 90°, for panel 4, 150°, for panel 5, 180°, for panel 6, −120°, for panel 7, −90°, and for panel 8, −30° from the $[11\bar{2}]$ step-down direction. The solid arrow in panel 5 indicates the IPSW of an antiband parallel to the step-down direction (also the dc direction) and white arrows in panels 4 and 6 indicate the IPSW of antibands whose ridges are parallel to the corresponding dc directions.

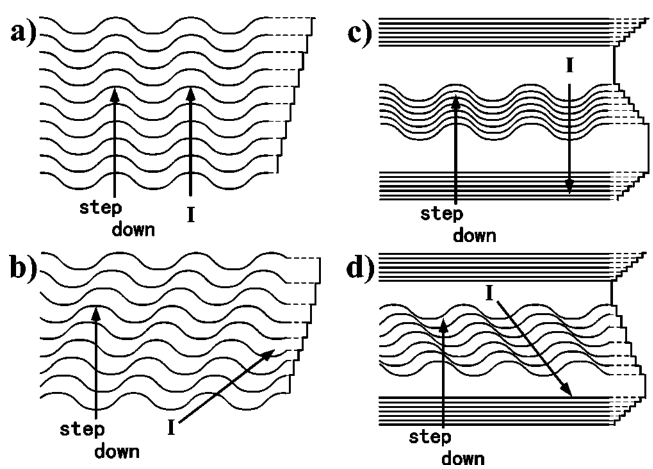


FIG. 2. Schematic drawings of (a) the IPSW when the dc is fed in the step-down direction, (b) the IPSW when the dc is fed with an angle from the step-down direction, (c) step bands and the IPSW of an antiband when the dc is fed in the step-up direction, and (d) step bands and the IPSW of an antiband when the dc is fed with an angle from the step-up direction.

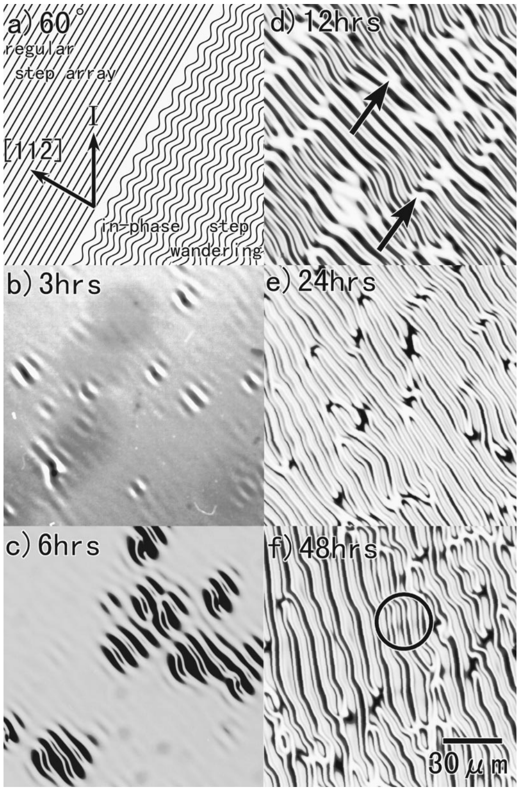


FIG. 3. A series of optical micrographs that show the time evolution of the IPSW annealed at 1100 °C with a deviation angle of 60°. (a) A schematic drawing showing the orientation relations in the experiments and a reproduction of the figures. Note that the direction of the ridges changes from (b) to (f). Arrows in (d) indicate branches of the ridges and a circle in (f) indicates a region where the ridge direction is parallel to the dc direction.

rection. The step arrangement in panel 4 of Fig. 1 is schematically shown in Fig. 2(d). This character is different from the cases of dc fed not parallel to the step-down direction (panels 2 and 8 of Fig. 1) with the same annealing time. This suggests a difference in the formation mechanisms for IPSW in the step-up current region and the step-down current region, which was also suggested from the appreciable difference in the period of the wandering steps in Ref. 23. When the dc was fed nearly parallel to the step direction (panels 3 and 7 of Fig. 1) dark and bright contrast regions are seen only locally. Step instability when the current is parallel to the step direction will be discussed in Sec. III C.

### B. Time evolution of the IPSW with a current 60° from the step-down direction

Figure 3 reproduces a series of optical micrographs showing the time evolution of IPSW annealed at 1100 °C. Figure 3(a) schematically shows the orientational relations in the experiments and the reproduction of the figures. The dc was fed in the upward direction in the figure, 60° from the step-down direction ([11$\bar{2}$] direction), panel 2 in Fig. 1. The upper-left part of Fig. 3(a) shows a regular array of steps, while the lower-right part shows the IPSW with ridges parallel to the step-down direction which is expected when a current is parallel to the step-down direction. The annealing times are 3 h [in Fig. 3(b)], 6 h [in 3(c)], 12 h [in 3(d)], 24 h [in 3(e)], and 48 h [in 3(f)]. In 3(b) and 3(c) IPSW is seen only locally on the surface, which clearly shows nucleation of IPSW regions.[27] In Fig. 3(d) the IPSW pattern covers the whole surface and branches of the ridges indicated by arrows are seen.[22,27] They are expected to form when IPSW patterns with different phases meet during their growth. At the initial stage ridges are in the direction between the step-down and the dc directions as in the case of Fig. 2(c). However, from Figs. 3(d) to 3(f) they gradually change their directions towards the dc direction. In 3(f) there are some ridges indicated by a circle that have become parallel to the dc direction. It should also be noted that the number of branches decreases as a function of time.

The time evolution of the IPSW for the case when the dc direction is tilted from the step-down direction can be schematically drawn as in Fig. 4. At the initial stage, wandering steps appear locally on the surface[27] similarly to when the dc is fed in the step-down direction[21] as indicated by a circle in Fig. 4(a). At this stage the direction of the ridges is closer to the over all step-down direction. After several hours (more than 6 h) of annealing the IPSW covers the whole surface and the ridge direction gradually changes to the dc direction as shown in Fig. 4(b) and the steps come partly close to each other. Because the steps cannot cross each other, the sinusoidal form of the wandering steps should be asymmetric as shown in Fig. 4(c). It should also be noted that this kind of topographic change needs a rearrangement of the ridges by the creation and annihilation of pairs of branches of the ridges, leading to the overall decrease of branches as mentioned above.

For quantitative studies of time evolution, the ridge separation $d$ and the angle $\phi$ between the ridge direction and step-down direction, which are shown in Fig. 4(b), were measured from the series of images. This was done by fast Fourier transform of the images as noted before.[23] The results of time evolution of angle $\phi(t)$ and the separation $d(t)$ are given in Figs. 5(a) and 5(b), respectively. It can be seen from Fig. 5(a) that the angle $\phi(t)$ is small with a large fluctuation for the first few hours of annealing due to the fact that the IPSW has not covered the whole surface as seen in Figs. 3(b) and 3(c). However, after a few hours it gradually increases and approaches 60°. It can be seen from Fig. 5(b) that the separation $d(t)$ slowly increases from 7.5 to 9.5 $\mu$m and the change is not as drastic as the angle $\phi(t)$. From the different behaviors in changes of the values of $\phi(t)$ and $d(t)$, it can be said that each wandering step cannot maintain a sinusoidal form and becomes asymmetric, as was schematically shown in Fig. 4(c). Although each step is not sinusoidal in form, its step period in shape $D$ $(=d/\cos\phi)$ as in Fig. 5(b) can be calculated. The evaluated values of $D(t)$ are also given in Fig. 4(b). The period at the initial stage is similar to that of the IPSW formed for $\phi=0$ and at 1100 °C.[23] However, after about 10 h the period becomes larger. It must be noted here again that the period of wandering steps is not that of the surface topograph (in other words the spacing of the ridges) when the current is not parallel to the step-down direction.

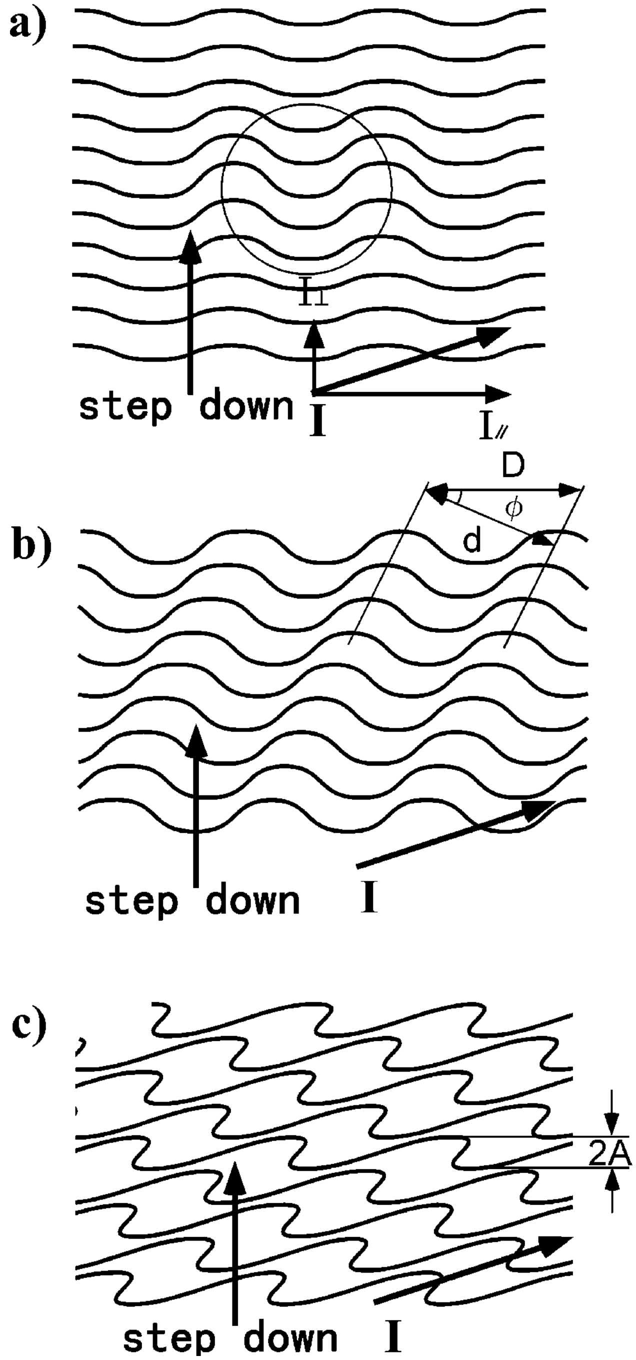


FIG. 4. Schematic drawings of the time evolution of the IPSW when the dc is fed in a direction with an angle from the step-down direction. The circle in (a) indicates the nucleation of the IPSW. (b) and (c) show the intermediate and final stages of IPSW, respectively. For quantitative studies, time evolutions of the ridge separation $d$, period $D$, and amplitude $A$ of individual wandering steps and the angle $\phi$ between the step-down direction and the ridge direction shown in (b) and (c) were studied.

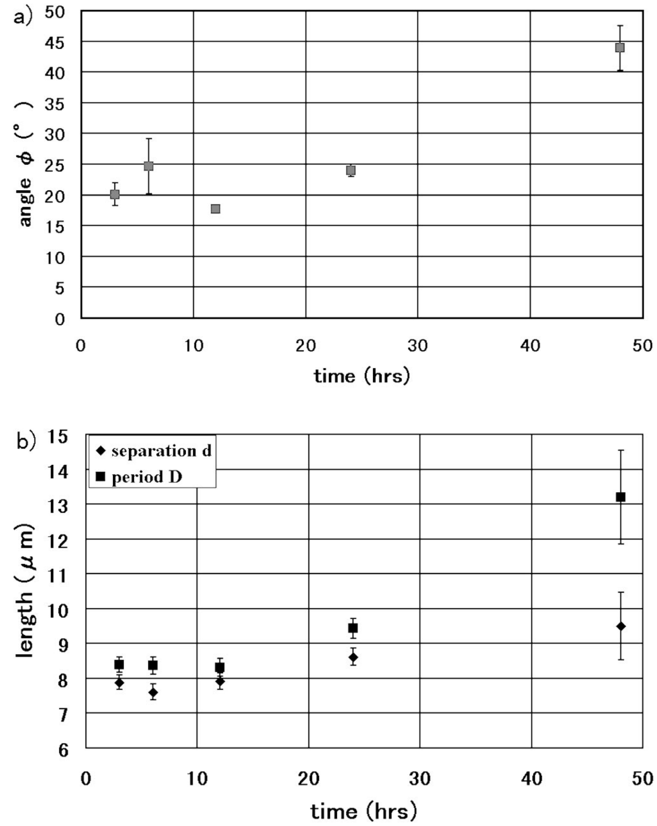


FIG. 5. A graph of the time evolution of (a) the angle $\phi(t)$ and (b) the separation $d(t)$ and the calculated wandering period $D(t)$ shown in Fig. 4(b).

From the time evolution of the period $d(t)$ and the angle $\phi(t)$ it can be concluded that wandering steps changes from a sinusoidal shape to an asymmetric shape when the heating current has a component parallel to the mean step direction.

Figure 6 reproduces micrographs of the same specimens in Fig. 3 taken by the cofocal laser microscope. All images are reproduced so that the mean ridge direction is vertical in the images. Depths ($H$) between the ridges and the valleys were measured from the profiles taken along white horizontal lines. For example, the depths of the ridge indicated by an arrow in each image in Fig. 6 are (a) 0.2, (b) 0.2, (c) 0.3, (d) 0.5, and (e) 0.6 $\mu$m. It is seen that the depth becomes deeper with time. The time evolution of the depth $H(t)$, averaged over the surface, is given in Fig. 7(a). It can be seen that it increases to a saturated value of about 0.5 $\mu$m. This is very close to the depth when the dc is fed parallel to the step-down direction.[21]

The average amplitude $A$ of wandering steps in the IPSW pattern shown in Fig. 4(c) was estimated from the measured depth $H$ as follows. The mean depth $H$ was measured from the profiles in the direction perpendicular to the ridges. The value is nearly equal to the depth measured from a profile in the direction of the mean step direction (perpendicular to the step-down direction). Since the mean step-step distance $l$ along the step down direction is $h/\tan\theta$, where $h$ is the height of the single step and $\theta$ is the miscut angle of the specimen (5°), the number $N$ of steps in a distance of $2A$ along the step-down direction is given by $2A/l = 2A\tan\theta/h$. Since $Nh = H$ we obtain $2A = H/\tan\theta$. The time evolution of the amplitude is plotted in Fig. 7(b). It is seen that the amplitude $A(t)$ seems to be saturated at around 2.5–3.0 $\mu$m.

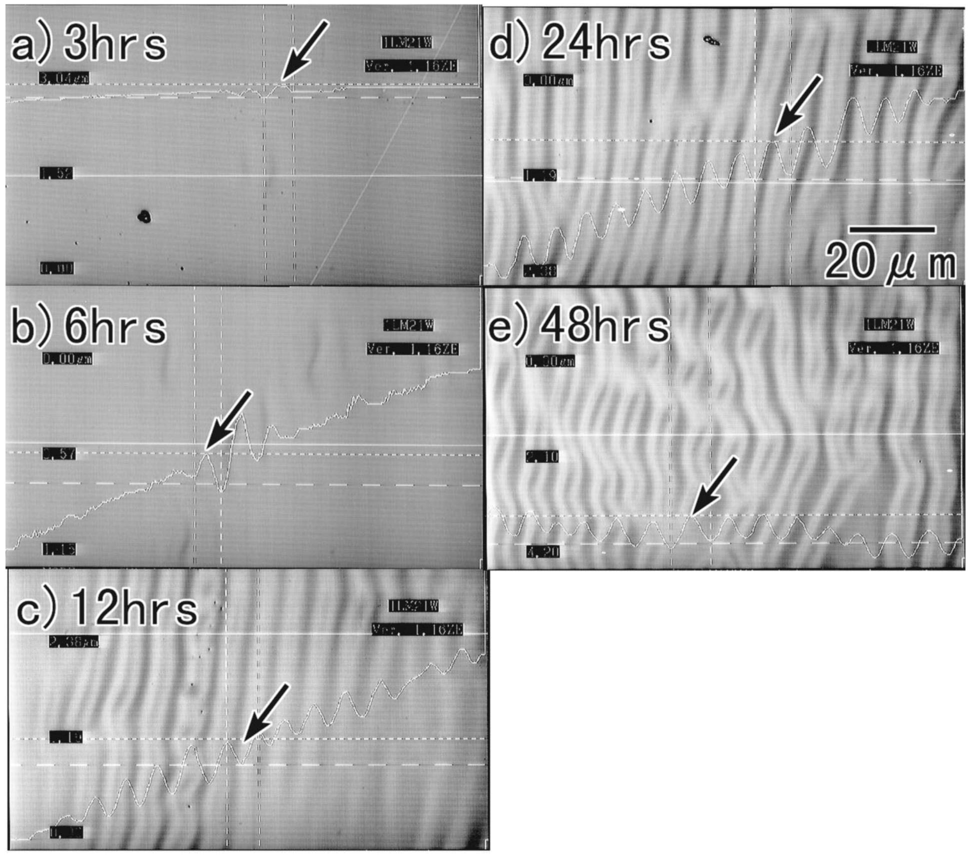


FIG. 6. A series of micrographs taken by the cofocal laser microscope at various stages of annealing. A wavy line in each image shows the surface depth profile along a horizontal white line (see also Fig. 10). The depths of the valleys from the ridges indicated by arrows are (a) 0.2, (b) 0.2 $\mu$m, (c) 0.3 $\mu$m, (d) 0.5 $\mu$m, and (e) 0.6 $\mu$m.

### C. Step instability under a heating current parallel to the step direction

Figure 8 shows wide area micrographs of the surfaces shown in panels 3 and 7 of Fig. 1, which were annealed at 1100 °C for 24 h with the dc fed parallel to the step directions. As mentioned in Sec. III A, both in Figs. 8(a) and 8(b) periodically ordered bright and dark bands with contrast gradually changing are seen to be formed locally. The contrast of these local regions is not uniform. Some of them have strong contrast but some of them have relatively weak contrast. Between these locally formed regions bright and dark bands with very weak contrast are seen. Directions of the weak contrast bands are about 25° from the current direction towards the step-down direction in both 8(a) and 8(b). These deviation angles are seen to be small in regions with stronger contrast. The intermediate contrast regions, such as indicated by arrows, are similar in shape in 8(a) and 8(b). They are like those seen in Fig. 3(b). However, in Fig. 8 they are asymmetric in shape (see Fig. 9) depending on the current directions that are from left to right in Fig. 8(a) and from right to left in Fig. 8(b).

The topographic nature of these bright and dark bands is not a step band but is considered to be the IPSW as schematically shown in Fig. 9. The figure shows locally nucleated IPSW with shifts of ridges mentioned above. Steps are heavily asymmetric. The directions of the ridges cannot approach the current direction because it is also the direction of the overall step direction. The fact that locally nucleated IPSW regions have different contrasts suggests that nucleation is not at one definite stage of annealing but it takes place continually during the annealing process. The fact that the directions of ridges in regions with strong contrast have smaller deviation angles from the current direction suggests that ridge directions in IPSW regions formed at the initial stage of annealing have a tendency to rotate to the current direction.

Figure 10 shows a micrograph of the sample in Fig. 8(b) taken by the cofocal laser microscope and a schematic drawing of the profile. An area where strong contrast is seen was selected. The profile is taken in the direction perpendicular to the ridge direction as done in Fig. 6. The ridge and valley structures are clearly seen. This also supports that the given contrasts are due to IPSW. The depth of the valley indicated by an arrow is about 0.4 $\mu$m. The depth of 0.4–0.6 $\mu$m is near to the value of the depth after 24 h annealing in Fig. 7(a) and in Ref. 21. This suggests that the nucleation of the IPSW structure takes place at an early stage of annealing. It is probable that weak contrast regions were nucleated in later stages of annealing.

## IV. DISCUSSION

From the studies on the effects of dc heating at 1100 °C (range II) on 5° off specimens with current directions devi-

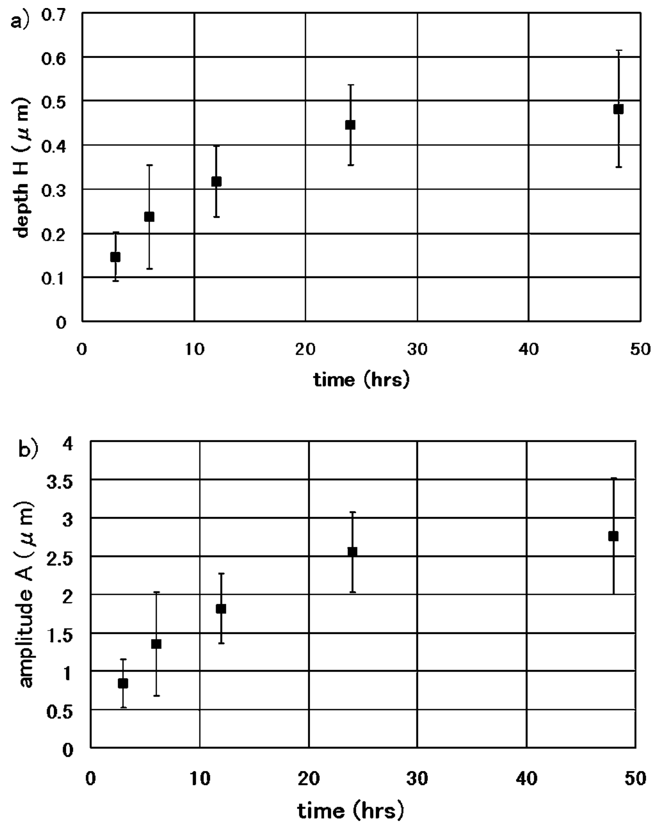


FIG. 7. Graphs that show the time evolution of (a) the depth $H(t)$ and (b) the average amplitude $A(t)$ of an individual wandering step. Saturation of their values is noted.

ated from the step-down or step-up directions and on the time evolution of IPSW (in the case of the deviation angle of 60°) the following conclusions are made.

(1) The IPSW starts from locally formed IPSW regions and at later stages (12 h annealing) they cover the whole surface.

(2) Directions of ridges of IPSW are in the direction between the step-down direction and the current direction.

(3) The directions gradually change to the current direction as the annealing time increases.

(4) Directions of ridges of IPSW of antibands are always parallel to the current direction.

(5) Separation of ridges $d$ increases slightly to a value about 9 $\mu$m and the depth $H$ between the chains increases to a saturation value of about 0.5 $\mu$m.

(6) The saturation of $H$ results in a saturation of the amplitude of wandering of individual steps along the step-down direction.

(7) The period $D$ of wandering of individual steps increases as an increase of $d(t)$ and $\phi(t)$ (the angle between the step-down direction and the ridge direction).

(8) The increase of $\phi(t)$ under the saturation of $d$ and $H$ causes severe asymmetry of wandering of individual steps.

The results of when the current was fed parallel to the mean step direction are as follows,

(9) The IPSW regions are locally formed by heavily asymmetric wandering steps.

(10) Depth $H$ of the IPSW regions is about at its largest 0.4–0.6 $\mu$m, similar to those described in conclusion (5). Some regions have a shallow depth and between IPSW regions faint contrast of IPSW is seen even after annealing of 24 h.

(11) Directions of the ridges are about 25° from the current direction at the initial stage and have a tendency to reorient slightly to the current direction.

It was revealed that IPSW starts from locally formed IPSW regions (nucleation). This is also the case when the current was fed parallel to the step-down direction for the

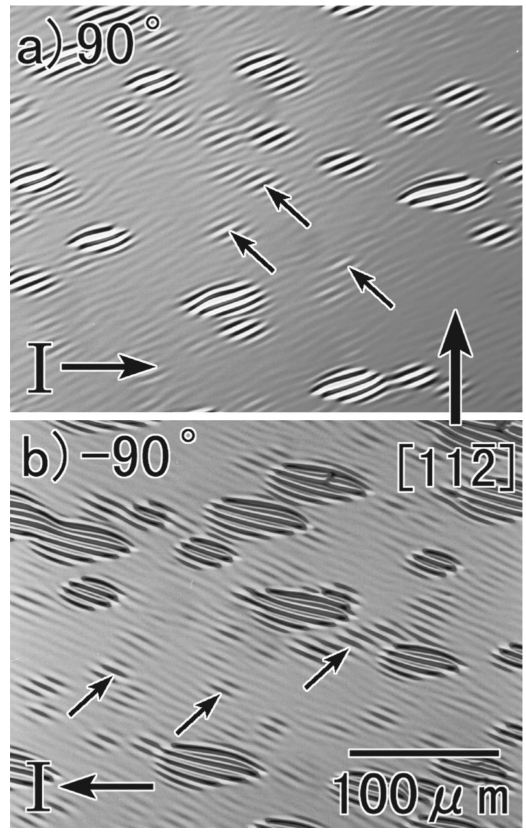


FIG. 8. Wide area micrographs of the surfaces shown in panels 3 and 7 of Fig. 1, annealed at 1100 °C for 24 h with the dc fed parallel to the step direction. Strong, weak, and intermediate contrasted bright and dark bands not parallel to the current directions are seen. They are due to IPSW (for details see the text).

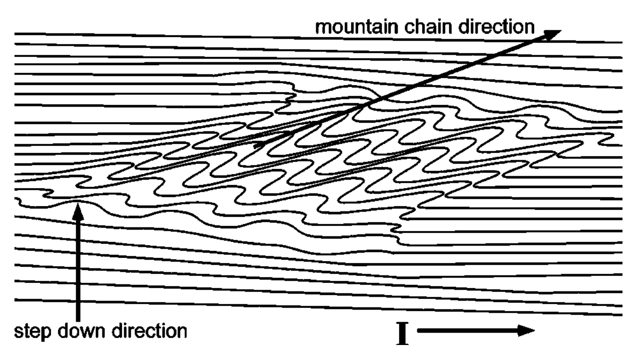


FIG. 9. A schematic drawing of the topographic nature of the locally formed IPSW regions, seen in Fig. 8. The wandering of individual steps is heavily asymmetric.

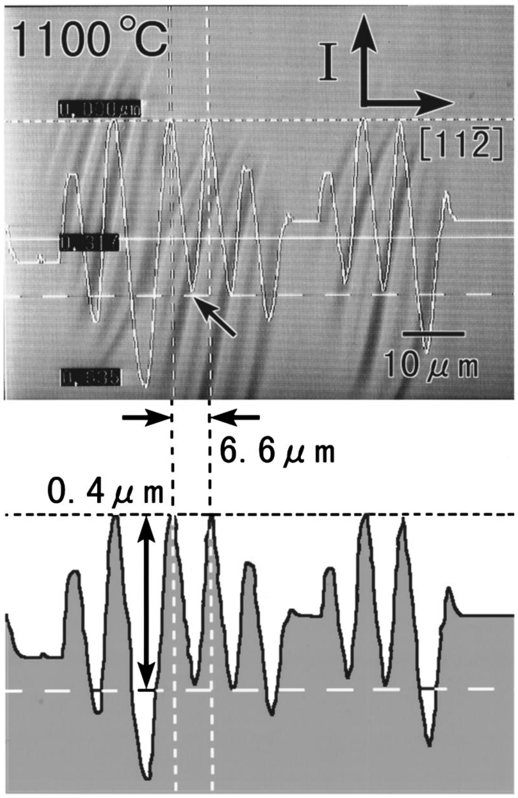


FIG. 10. A micrograph taken by the cofocal laser microscope of the sample in Fig. 8(b) and a schematic drawing of a profile along a white horizontal line in the micrograph. The valley indicated by an arrow in the micrograph is about 0.4 $\mu$m in depth and 6.6 $\mu$m in width.

same 5° specimen.[21,27] However, there is a difference of annealing time at which IPSW covers its whole surface. It is about 4 h when the current is parallel to the step-down direction,[21] while in the present case in Fig. 3, 6 h of dc annealing is still not long enough for the IPSW to cover the whole surface. This difference is considered to be due to a smaller $I_\perp$ (a smaller drift force) component of the dc current perpendicular to the overall step direction in the present case than that in Ref. 21. The fact that the extreme cases of $I_\perp \sim 0$ in panels 3 and 7 of Fig. 1 (Fig. 8) need longer time supports that $I_\perp$ plays an important role for the nucleation of IPSW. Other factors that affect nucleation are a step density (off-angle)[21] and a density of the pinning site of steps.[21,27] In the former case easy nucleation on low off-angle surface was noted. These are discussed in each paper.

Another point that should be discussed in relation to the nucleation is the shape of nucleated areas. Figure 3(b) and Fig. 8 show that they are elliptic with their longer axis perpendicular to the ridge direction, though they are distorted in Fig. 8 in the direction of the current. This fact indicates that IPSW expands more easily in the direction parallel to the step direction (perpendicular to the ridge) than parallel to the ridges. The distortion in Fig. 8 is due to the fact that the steps are parallel to the current. This characteristic can be traced in the distribution of branches of the ridges that are considered to be formed by the coalescence of IPSW regions with out-of-phase relations. For example, in Fig. 3(d) the chances to meet branches are more frequent when we move along the ridges than when we move perpendicular to them.

The direction of the ridges at the nucleation stage is close to the step-down direction rather than to the current direction. Then the direction gradually changes to that of the dc. This change would be due to the current component $I_\parallel$ (drift force component) parallel to the step direction. There should be an increase of a relative phase of neighboring steps: shifts of the wandering peaks of the lower side step to the $I_\parallel$ direction or shifts of those of the upper side step to antiparallel to the $I_\parallel$ direction. As mentioned before, the effect of $I_\parallel$ has been theoretically discussed for the wandering of an isolated impermeable step.[15] They concluded a shift of the wandering phase of the isolated step so as to move the wandering peaks in the direction antiparallel to the $I_\parallel$ direction during its receding. The theory cannot be applied to a step array system. The assumption of impermeable steps is also not made in the present case as will be discussed later. The fact that the reorientation of the ridge stops when the ridges becomes parallel to the current suggests that the reorientation is due to the current component ($I_{\perp r}$) perpendicular to the ridges and not to the component $I_\parallel$. The former component $I_{\perp r}$ causes step-down drift force (causing regular steps) and step-up drift forces (causing step bunching) periodically with a period $d$ [see Fig. 4(b)]. Therefore, $I_{\perp r}$ enhances the asymmetric shape of the wandering steps and it results in the reorientation of the ridges [from Fig. 4(b) to 4(c)]. The above discussion is not for an explanation of atomic processes for the reorientation but because the reorientation, hence asymmetric IPSW, is consistent with the observed step behaviors in range II.

Step bunching is an instability that takes place by an asymmetric diffusion on terraces perpendicular to the mean step direction. Thus, step bunching in the case of the dc parallel to the step direction is not expected because there is no such asymmetry. On the other hand, the IPSW is an instability that takes place by modulation of the diffusion field on terraces along the steps. Such modulation can be caused by the local fluctuation of the step shape from a straight one. When the drift force is parallel to the straight steps, modulation along the steps is not expected, though the diffusion field is asymmetric along the steps. However, this is not the case if the local fluctuation of the step shape takes place and the modulation of the diffusion field along the overall step direction, hence the IPSW, is expected. In the present experiments it was found that the fluctuation of step orientation, either by intrinsic thermal origins or extrinsic (due to the pinning site of steps) origins, causes step-down current locally and nucleation of heavily asymmetric IPSW (Fig. 9) takes place. From a geometrical limit, the ridge direction cannot be parallel to the current (mean step direction) and there is a definite angle between the two directions as seen in Fig. 8, which may depend on off-angles of the surfaces.

The ridge separation $d$ ($t = \propto$) after a slight increase from that at the initial stages is around 8 $\mu$m and is seen to be independent of the current direction, including the case where the current is parallel to the steps. This means that the period $D$ of individual steps is not a determining factor of the finally formed surface topograph after dc heating. Depth $H$

increases to a value about 0.5 $\mu$m (the amplitude of wandering of an individual step of about 2.5–3.0 $\mu$m), which is also the case when the current is parallel to the step direction as in Fig. 8 and is parallel to the step-down direction for the 5° off specimens.[21] Thus, it can be said that these values do not depend on the current orientation.

As seen at positions indicated by white arrows in panels 4 and 6 in Fig. 1, in the cases where the dc heating current has a step-up component, the ridges of IPSW of antibands are always parallel to the current direction independent of the growth stage (length of the ridges) of the IPSW. This is in strong contrast to the case of IPSW in the step-down current experiments. This should be due to the difference in the step configuration at the nucleation stage of IPSW. In the former case, wandering may nucleate from the fluctuation of a step at the bottom of an antiband. This step can form an asymmetric wandering shape on the wide terrace that is at the lower side of the antiband. In the latter case, on the other hand, nucleation may start from the wandering of several steps that are narrowly spaced.

Very recently theoretical considerations to explain IPSW under a drift force along the step-down direction have been done. Natori's group takes into account the preferential drift of adatoms along the steps which enhances wandering.[28] Their simulation could show IPSW although their wandering period is much smaller than the present observations. On the other hand, Sato and Uwaha considered permeable steps.[26] They could show IPSW when the drift force exceeds a certain value. However, at present these theories are not ready for qualitative and quantitative comparisons with our experimental results. Further progress is expected.

## ACKNOWLEDGMENTS

This work was supported by Grant-in-Aid of Creative Research (No. 09NP1202) from the the Ministry of Education and by Grant-in-Aid from the Ministry of Education (No. 10044146). We are grateful for discussions with Professor A. Natori, Professor M. Uwaha, and Professor E. D. Williams about our experimental progress. We also thank Professor T. Matsuo, Professor T. Shibuya, Dr. Y. Terada, and Dr. M. Ohmiya for their kindly offering the use of the optical microscope and the cofocal laser microscope.

*Present address: Department of Physics, University of Maryland, College Park, Maryland 20742-4111.

[1] A. V. Latyshev, A. L. Aseev, A. B. Krasilnikov, and S. I. Stenin, Surf. Sci. **213**, 157 (1989).
[2] A. Yamanaka, H. Ohse, and K. Yagi, *Proceedings of the XIIth International Congress for Electron Microscopy* (San Francisco Press, San Francisco, 1990), p. 366.
[3] A. Yamanaka, H. Ohse, H. Kahata, and K. Yagi, *The Structure of Surfaces III*, edited by S. Y. Tong *et al.* (Springer-Verlag, Berlin, 1991), p. 502.
[4] H. Yamaguchi and K. Yagi, Surf. Sci. **287/288**, 820 (1993).
[5] H. Kahata and K. Yagi, Jpn. J. Appl. Phys., Part 1 **28**, L858 (1989).
[6] H. Kahata and K. Yagi, Jpn. J. Appl. Phys., Part 1 **28**, L1042 (1989).
[7] A. Natori, Jpn. J. Appl. Phys., Part 1 **33**, 3583 (1994).
[8] A. Natori, H. Fujimura, and M. Fukuda, Appl. Surf. Sci. **60/61**, 85 (1992).
[9] S. Stoyanov, J. Appl. Phys. **30**, 1 (1991).
[10] D. Kandel and E. Kraxias, Phys. Rev. Lett. **76**, 1114 (1996).
[11] A. V. Latyshev, A. B. Krasilnikov, and A. L. Aseev, Surf. Sci. **311**, 395 (1994).
[12] Y.-N. Yang, E. S. Fu, and E. D. Williams, Surf. Sci. **356**, 101 (1996).
[13] K. Thurmer, D.-J. Liu, E. D. Williams, and J. D. Weeks, Phys. Rev. Lett. **83**, 5531 (1999).
[14] M. Uwaha and M. Sato, Surf. Rev. Lett. **5**, 841 (1998).
[15] M. Sato, M. Uwaha, and Y. Saito, Phys. Rev. Lett. **80**, 4233 (1998).
[16] J. J. Metois and M. Audiffren, Int. J. Mod. Phys. B **11**, 3691 (1997).
[17] S. Stoyanov, Surf. Sci. **416**, 200 (1998).
[18] D.-J. Liu and J. D. Weeks, Phys. Rev. B **57**, 14 891 (1998).
[19] D.-J. Liu, J. D. Weeks, and D. Kandel, Phys. Rev. Lett. **81**, 2743 (1998).
[20] M. Degawa, H. Minoda, Y. Tanishiro, and K. Yagi, Jpn. J. Appl. Phys., Part 1 **38**, 308 (1999).
[21] H. Minoda, I. Morishima, M. Degawa, Y. Tanishiro, and K. Yagi, Surf. Sci. (to be published).
[22] M. Degawa, H. Minoda, Y. Tanishiro, and K. Yagi, Surf. Rev. Lett. **6**, 977 (1999).
[23] M. Degawa, H. Minoda, Y. Tanishiro, and K. Yagi, J. Phys.: Condens. Matter **11**, L551 (1999).
[24] Y. Homma and P. Finne, J. Phys.: Condens. Matter **11**, 9879 (1999).
[25] M. Degawa, H. Minoda, Y. Tanishiro, and K. Yagi, Surf. Sci. **461**, L528 (2000).
[26] M. Sato, M. Uwaha, and Y. Saito, Phys. Rev. B **62**, 8452 (2000).
[27] M. Degawa, K. Thuermer, I. Morishima, H. Minoda, K. Yagi, and E. D. Williams (unpublished).
[28] N. Suga, J. Kimpa, Nan-Jian Wu, H. Yasunaga, and A. Natori, Jpn. J. Appl. Phys., Part 1 **39**, 4412 (2000).