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LETTER TO THE EDITOR

Temperature dependence of period of step wandering formed on Si(111) vicinal surfaces by DC heating

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Abstract. Wandering of an array of steps in phase on Si(111) vicinal surfaces (5° off toward the [11$\bar{2}$] direction) formed by DC heating at temperatures $1000 < T < 1180$ °C was studied. Periods of the step wandering formed on step-down current regions depended on the temperature and had a maximum at around 1100 °C. This also supports the view that the wandering is due to the DC heating effect. The periods were also measured for the step wandering of anti-bands on terraces between step bands formed by DC heating with a step-up current and we found that the periods were appreciably smaller than that in the step-down current regions.

Heating with a direct current through an Si crystal induces a variety of surface topographies on its clean surface which depend on the heating current directions, surface orientations and temperature. Such a phenomenon, called the current effect, is caused by a drift force on adatoms on the surface. The current effect on Si(111) surfaces is summarized as follows [1–3]. (1) Above the surface structure phase transition temperature between the 1×1 and 7×7 structures, a step-up current (perpendicular to the step array) stabilizes a regular array of steps (figure 1(a)), while a step-down current destabilizes the regular array of steps and induces step bunching (figure 1(b)). (2) The current direction for step bunching reverses at least twice, at about 1000 °C and 1180 °C. In the present paper we denote these temperature ranges I, II and III. In range II (1000 °C $< T <$ 1180 °C), which we studied in detail in the present work, a step-up current induces step bunching. (3) Below the surface structure phase transition temperature the current effect is complicated [3, 4].

Recently, we studied the current effect on vicinal surfaces with off angles up to about 14° by using a (111) surface with a cylindrical groove along the [1$\bar{1}$0] direction (steps are [11$\bar{2}$] and [$\bar{1}\bar{1}$2] steps). We found that the same bunching behaviour was found on these vicinal surfaces. In addition, we found step wandering as shown in figure 1(c) in the step-down current regions in range II [5]. Since in this case all of the wandering steps are in phase, we denote this 'in-phase step wandering'. In-phase step wandering was also seen on terraces between step bands formed in the step-down current regions in range II. The wandering was in the regions of anti-bands where the current was a step-down current locally. Thus it was concluded that step wandering is formed by direct current to the step-down direction [6]. However, the mechanism of the step wandering of anti-bands [6] is considered to be different from that on the step-down current regions because in the former case flat terraces are adjacent to the anti-bands. Formation of the anti-bands was first reported by Latyshev *et al* [7]; however, they did not report the step wandering subsequently formed after the anti-band formation.

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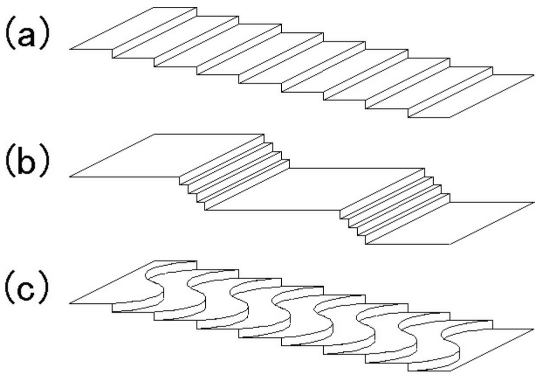

Figure 1. Schematic drawings of step bunching (b) and in-phase step wandering (c) from a regular array of steps (a).

Many theoretical works on step bunching under a drift force on adatoms on the terrace have been reported [8–11] and have tried to explain the reversals of the current effect. A reversal of the current effect at a certain temperature means either that the drift force decreases and changes its sign at the temperature resulting in the reversal of the current effect under the same bunching mechanism, or that the drift force does not changes its sign but two different bunching mechanisms interchange at the temperature. In both cases it can be said that the current effect is expected to be stronger when the temperature is further from the temperature of the reversal. For example, in range II the current effect should be strong at around 1100 °C which is the middle of the temperature range, and weak on both sides. Few theoretical works have been done on the step wandering under the drift force and they are for the wandering of a single isolated step [12]. Theoretical works on step wandering of an array of steps are needed and for them more sound experimental evidence is needed. In the present letter we briefly report the temperature dependence of the periods of the step wandering and a difference of the period due to different wandering mechanisms.

Specimens (B doped, few Ω cm, $7 \times 1 \times 0.3$ mm^3 in size) which have 5° off surfaces from the (111) plane inclined toward the [11$\bar{2}$] direction ([11$\bar{2}$] steps on the surfaces) were annealed by DC heating in temperature range II for about 24 h after flash cleaning at 1200 °C. As noted before [2, 5], there are no differences between the current effects for the [11$\bar{2}$] and [$\bar{1}\bar{1}$2] steps. So the present results on the [11$\bar{2}$] steps also hold for the [$\bar{1}\bar{1}$2] steps as well. The surfaces were observed by an optical microscope with no emissivity corrections.

Figure 2 shows optical microscope images of surfaces after annealing at 1100 °C, (a) with a step-up current and (b) with a step-down current. In (a) horizontal lines are step bands formed by step bunching. Bright areas are terraces between the step bands. Vertical line images between the step bands are due to step wandering of anti-bands formed on the terraces. Some terraces show images of straight anti-bands or embryos of shortly segmented step wandering. Some terraces stay nearly flat without anti-band formation. In (b) step wandering is seen as vertical lines all over the surface. The surface topography is like an array of mountain chains. Bright areas are slopes of the mountain chains inclined to the left and dark areas are to the right. It is noted that the average period of step wandering, the interval of the vertical line images, in (a) is narrower than that in (b), which is considered to reflect a difference of the mechanisms of the step wandering.

Figure 3 reproduces micrographs of the surfaces after annealing by step-down current for 24 h at (a) 1050 °C, (b) 1075 °C, (c) 1100 °C, (d) 1125 °C and (e) 1150 °C. It is seen that the

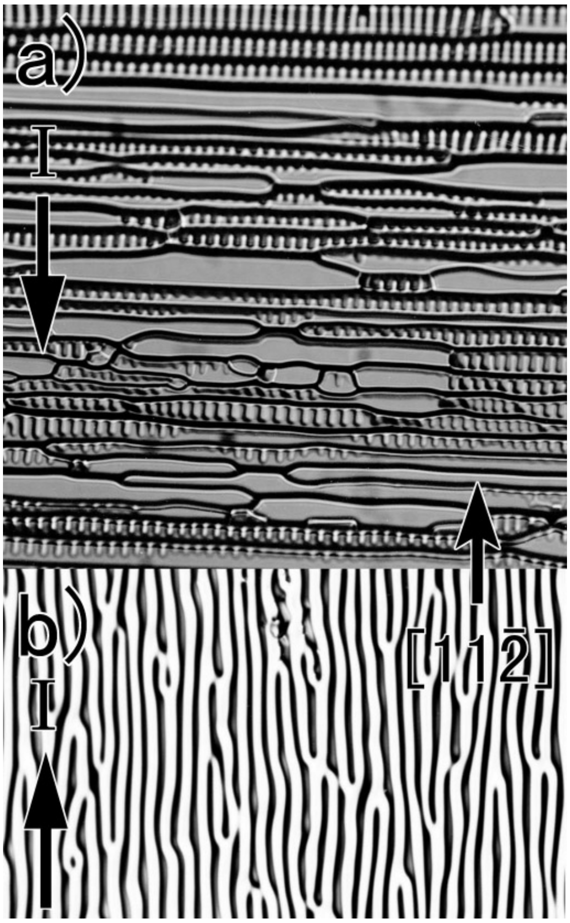

Figure 2. Optical micrographs of 5° off Si surfaces after annealing at 1100 °C for 24 h (a) by a step-up direct current and (b) by a step-down direct current. Step wandering in (b) and step bunching together with step wandering of the anti-bands between the step bands in (a) are seen.

wandering period increases from (a) to (c) and decreases from (c) to (e). Another thing to be noted is that the line images due to step wandering show branches. These branches are considered to be formed when areas of the step wandering formed nearby meet each other. Some of them can annihilate by collision with opposite type branches. Such places are marked by circles in the figure. Faint dark lines indicated by arrows are considered to be ‘low mountain chains’ which are going to disappear. The density of branches decrease by a factor of two from (a) to (b) partly due to the increase of the wandering period and partly due to the decrease of nucleation sites of the step wandering. From (c) to (e) the density does not change due to cancellation of the two effects: the decrease of the period and the decrease of the nucleation site. Arrowheads in (a) indicate contamination on the surface mainly of SiC. It can be seen that the amount of contamination decreases as the temperature increases. It is likely that this contamination would change the wandering period. However it was found that the periods were all the same on surfaces with different amounts of contamination, which leads us to conclude that contamination does not affect the wandering period.

For the quantitative analysis of the period of the step wandering, fast Fourier transformation

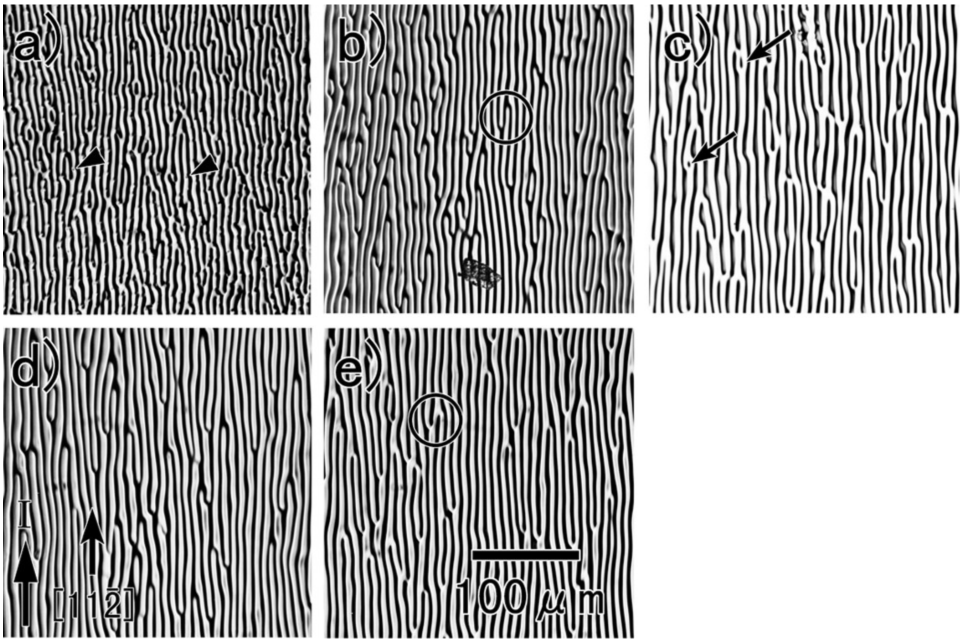

Figure 3. Optical micrographs of 5° off Si surfaces after annealing by a step-down current for 24 h (a) at 1050 °C, (b) at 1075 °C, (c) at 1100 °C, (d) at 1125 °C and (e) at 1150 °C. The period of step wandering, the mean spacing of the lines, is seen to depend on the annealing temperature.

(FFT) of the images was carried out and results are shown in figure 4. It shows line scans of each FFT pattern through the origin along the direction perpendicular to the step wandering lines. Since the peak positions of the FFT patterns are not well defined, the middle point of the two half-maximum positions of each peak was used as the peak position. From the reciprocal distance of two main peaks, we obtain the average period of step wandering at each temperature.

Several runs of experiments including the results on the cylindrical grooves gave the temperature dependence of the period of step wandering in range II as shown in figure 5. It is quantitatively concluded that the period increases with an increase of the annealing temperature and has a maximum value of about 8.2 μm and decreases with further increase of the temperature. The fact that the period depends on temperature in range II and is small as the temperature goes to range I or to range III indicates that step wandering is due to the current effect and its period depends on the 'strength' of the current effect.

Figure 5 was obtained mainly from the experiments on the 5° off specimen. Studies on the cylindrical grooves showed that the period of step wandering does not depend on the off angle from the (111) surface. Thus, the results in figure 5 represent a general trend in region II.

Homma *et al* [13] measured step separation on nearly flat (111) surfaces and showed its characteristic temperature dependence. The measured values are considered to be closely related to the diffusion length on the surfaces. Their results showed that it decreases monotonically in region II from around 47 to 10 μm, which is quite different from the temperature dependence of the step wandering period. The measured step separations are also much larger than the measured periods of the wandering in our study.

In figure 2, narrower periods of the step wandering of the anti-bands between the step bands in (a) than those on the step-down current regions in (b) were noted. From FFT of

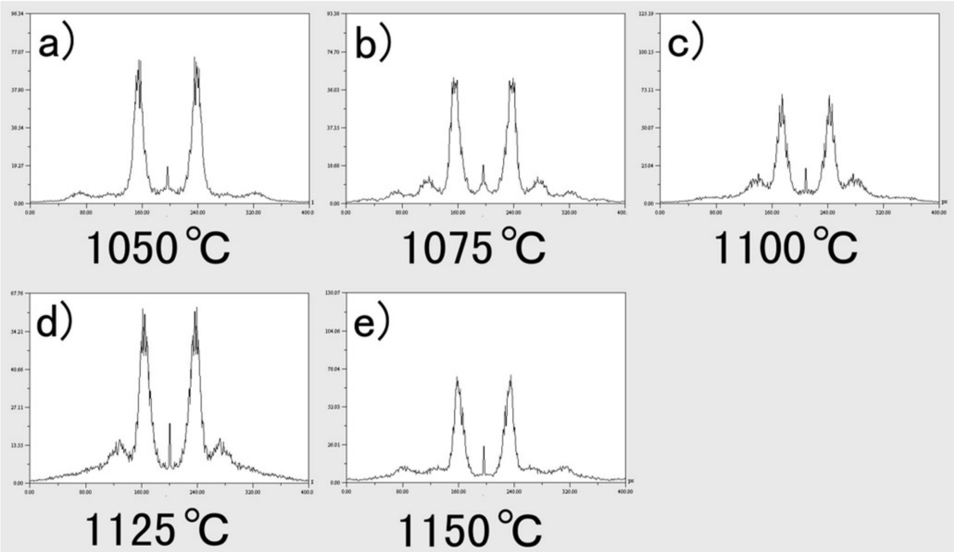

Figure 4. One dimensional scans through the origins of FFT patterns of the optical micrographs in figure 3. Sharp peaks due to mean spacing of the line images due to step wandering are noted in each pattern. Peak spacing decreases from (a) to (c) and increases from (c) to (e).

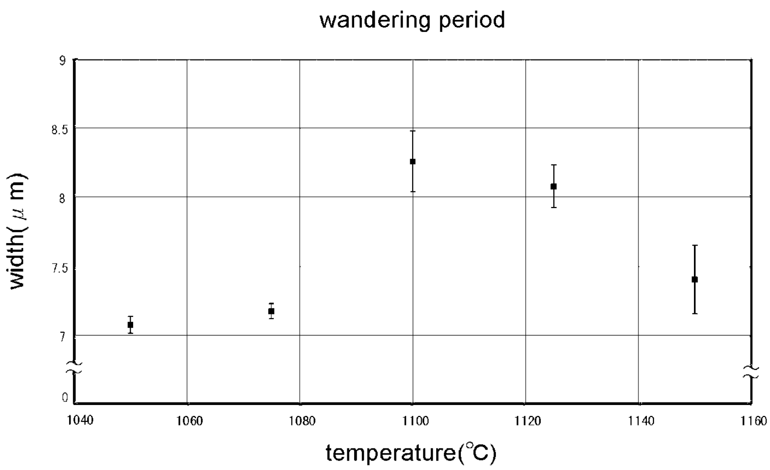

Figure 5. A graph which shows a temperature dependence of the period of step wandering in range II obtained from figure 4 and other experimental results.

such images the average period at 1100 °C was measured to be 6.4 μm which is smaller not only than that at 1100 °C in figure 5 but also than those at other temperatures in range II. The difference is considered to be due to a difference of the step wandering mechanism, although the mechanism in the step-down current regions is not clear at present.

Theoretical approaches which can explain the wandering period and its temperature dependence are expected.

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References

[1] Latyshev A V, Aseev A L, Krasilnikov A B and Stenin S I 1989 *Surf. Sci.* **213** 154

[2] Yamanaka A, Ohse H, Kahata H and Yagi K 1991 *The Structure of Surfaces III* ed S Y Tong *et al* (Berlin: Springer) p 502

Yamanaka A, Ohse H and Yagi K 1990 *Proc. 12th Int. Congr. for Electron Microscopy* (San Francisco: San Francisco Press) p 366

[3] Yamaguchi H and Yagi K 1993 *Surf. Sci.* **287/288** 820

[4] Homma Y, McClelland R J and Hibino H 1990 *Japan. J. Appl. Phys.* **29** L2245

[5] Degawa M, Nishimura H, Tanishiro Y, Minoda H and Yagi K 1999 *Japan. J. Appl. Phys.* **38** L308

[6] Degawa M, Minoda H, Tanishiro Y and Yagi K *Proc. 6th ICSOS (Vancouver)* submitted

[7] Latyshev A V, Litvin L V and Aseev A L 1998 *Appl. Surf. Sci.* **130–132** 139

[8] Natori A 1994 *Japan. J. Appl. Phys.* **33** 3583

[9] Stoyanov S 1991 *Japan. J. Appl. Phys.* **30** 1

[10] Kandel D and Kaxiras E 1996 *Phys. Rev. Lett.* **76** 1114

[11] Liu D-J and Weeks J D 1998 *Phys. Rev.* B **57** 14 891

[12] Uwaha M and Sato M 1998 *Surf. Rev. Lett.* **5** 841 and references therein

[13] Homma Y, Hibino H, Ogino T and Aizawa N 1998 *Phys. Rev.* B **58** 13 146