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Atomic Terraces and Steps on (100) Silicon Surfaces Observed by Reflection Electron Microscopy

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Atomic steps on a substrate surface interrupt the two-dimensional layer-by-layer growth in MBE and introduce the anti-phase domain(APD) in polar on nonpolar epitaxial growth. Step structures on (100) semiconductor surfaces have been studied intensively, by more or less indirect methods, so far. Surface imaging by reflection electron microscopy(REM) contains far more information about step structures than any other techniques, as demonstrated previously for the case of (111) silicon surfaces[1]. This paper reports on the direct observation of reconstructed surfaces, well developed smooth terraces and mono-layer steps on (100) silicon surfaces by ultra high vacuum(UHV) REM.

The samples were cut from (100) silicon wafers. The surface tilt was confirmed to be between 0.1 and 0.3° by X-ray diffraction. They were cleaned successively in boiled tri-chrol-ethylene and H_2SO_4:H_2O_2:H_2O etch and rinsed in de-ionized water. The REM observations were made with a 100kV UHV transmission electron microscope which was used in the previous observation on (111) surfaces. The pressure around the specimen was of the order of 10^{-8} Torr during observation. The sample was mounted on a single tilt resistive heating stage. Cleaning in UHV was accomplished by heating the sample. The sample was then brought to the observation temperature.

Figure 1 shows images of a clean (100) surface in [110] azimuth at about 1000°C. In Fig.1a, an image by a specular reflection, many bright regions as wide as several microns are observed separated by horizontal dark bands. Steps which has clearly been observed on the (111) silicon surfaces[1] are not observed within the regions. So, these regions are atomically smooth terraces. The terrace width is several microns, while it is estimated to be about 1000A from the surface tilt and bi-layer step height. It is concluded that the atomically smooth terraces several microns wide are developed on the (100) surfaces by the annealing. The largest terrace width reported so far is about 4000 A estimated by the RHEED technique[2].

Figure 1b shows a dark field image of the same area as Fig.1a by a half order reflection. Note the reverse contrast from Fig.1a over the whole area. The most striking is the periodic black-and-white contrasts indicated by arrows. The bright regions are identified as the 2x1 reconstructed domains.

The dark regions must be the 1x2 reconstructed domains since the 1x1 unreconstructed surface may not be stable on (100) sufaces, though it was suggested to be present on the surface largely inclined from (100)[3]. Both reconstructed domain widths are estimated to be about 1000A. Boundaries between both reconstructions must be composed of mono-layer steps.

The bright regions dominant in Fig.1a are also the 1x2 reconstructed terraces. It means that the sample surface tends to form single domain by the annealing. Single domain formation on the (100) silicon surface[2] and the resultant APD elimination in GaAs on silicon[4] have been observed by RHEED. The advantage of REM is that even a small amount of two-domain structure may be clearly observed.

Surface imaging by reflection electron microscopy was performed on the (100) silicon. It is revealed for the first time that the atomically smooth terraces several microns wide and periodic array of 2x1 and 1x2 reconstructed domains are developed by the annealing. The latter is the most direct evidence of the presence of mono-layer steps so far. RHEED or cross sectional TEM technique can neither observe such large terraces or clarify such a complicated step structure as shown above. The results demonstrate that the REM is the indispensable technique in understanding the mechanism of atomic layer epitaxy and polar on nonpolar epitaxy.

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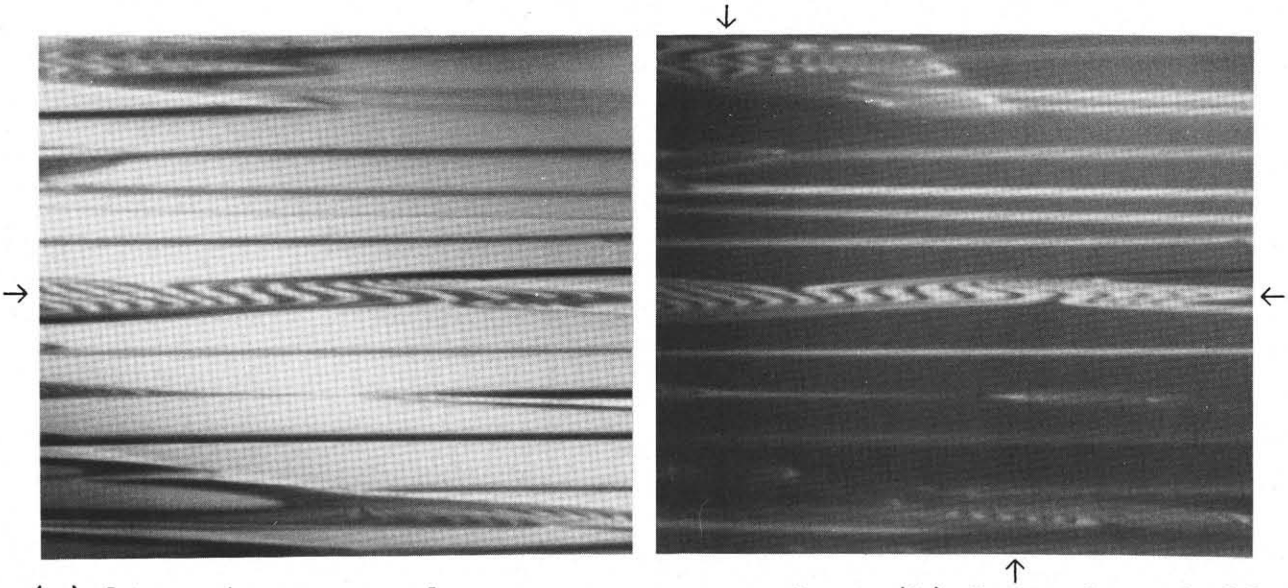

(a) Image by a specular reflection.

1μm

(b) Image by a half order reflection.

Fig.1 Reflection electron micrographs of a (100) silicon surface.