PRIORITY COMMUNICATION

ATOMICALLY FLAT LPE-GROWN FACETS SEEN BY SCANNING TUNNELING MICROSCOPY

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On GaAs ($\bar{1}\bar{1}\bar{1}$) facets grown by a slider-free LPE technique, atomically flat areas and growth steps 6.5 Å high have been verified by the novel scanning tunneling microscopy. Nomarski interference contrast micrographs give a mean distance of the steps of 6 μm. These extremely flat and structurally perfect surfaces are thus nearly free of steps in contrast to surfaces and facets previously prepared.

In crystal growth, the surface topography is of interest for studies of growth mechanisms and their relation to theory. By surface investigations, the properties of the grown crystals or crystalline layers can be related to the growth conditions, and thus help to optimize the performance of structural perfection- and homogeneity-sensitive devices and to achieve abrupt p–n junctions. Theoretical predictions and numerical simulations [1] as well as growth experiments and decoration techniques [2] have revealed large differences of surface structures. These depend on the growth method, growth temperature, supersaturation or material flux towards the surface, impurities and so forth. Also chemical and sputter etching and annealing procedures lead to various surface morphologies and surface reconstruction.

Direct quantitative techniques available to investigate the surface topography range from relatively simple stylus methods [3], optical interferometric and holographic methods and phase contrast microscopy developed by Zernike [4] to multiple-beam interferometry using fringes of equal chromatic order (FECO) [5] and scanning electron microscopy. These methods have resolutions to *either* about 10 Å height difference *or* 100 Å lateral distance. The *Scanning Tunneling Microscope* (STM) is a recently developed surface characterization tool [6] with a simultaneous lateral resolution of about 10 Å (at a maximum scan length of presently 0.2 to 1 μm) *and* height resolution of better than 1 Å. Scanning tunneling microscopy is based on tunneling through a vacuum gap between a tungsten tip and the conducting sample [7]. A feedback system keeps the tunneling current constant by piezoelectrically adjusting a constant tunneling distance d_T. As the piezodriven tungsten tip moves along the X- or Y-directions across the surface, the piezoelectric signal in the Z-direction describes the contour of the surface. Details on the STM are given elsewhere [6,7].

The measurements were done on the same GaAs ($\bar{1}\bar{1}\bar{1}$) facet described before [8]. Blue reflectance indicated surface oxide which therefore was dissolved by HCl. After etching, Nomarski microphotographs showed the same surface features as previously [8], indicating that oxidizing and subsequent etching does not roughen the facets appreciably. No further surface cleaning was applied in order to keep the growth surface as intact as possible. STM investigations of semiconductors require high electric fields (some volts over a gap of some 10 Å for quenching the Schottky layer) which lead to field-induced desorption of adsorbates and thus noisy signals. For noise reduction, a 100 to 200 Å Au film was sputter deposited, preserving the surface features seen by Nomarski (see below). In the following, we show

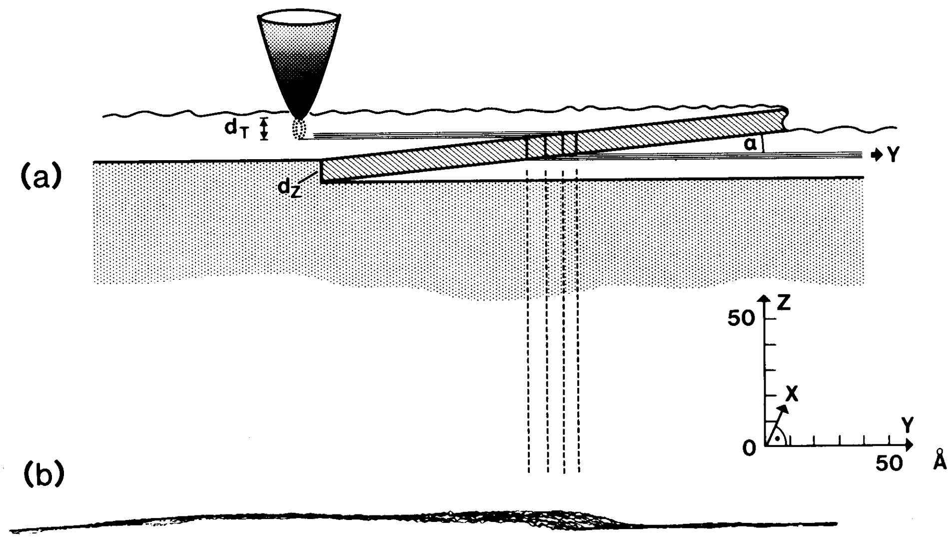

Fig. 1. (a) Schematic sample arrangement in front of the tunneling tip with the coordinates and the lateral and the height scales. The step of height d_Z makes the angle α with the scan direction Y. (b) Multiple STM scan showing an atomically flat surface with a step about 6.5 Å high on a LPE-grown GaAs $(\bar{1}\bar{1}\bar{1})$ facet.

the STM results of Au-coated facets, but the uncoated GaAs gave similar results.

Fig. 1a shows schematically the tungsten tip in front of the flat surface with a step of height d_Z. Several scans in the Y-direction give the contour lines shown in fig. 1b. The scans nearly overlap on the flat areas, whereas at the step, which makes an angle α with the Y-direction, the contour lines are better separated. The measured step height of 6 to 7 Å corresponds to a double layer of $2 \times d_{(111)} =$ 6.5 Å. It is interesting to note that both etching and the gold coverage retain the sharpness of the step to a great extent so that it appears only 20 Å wide. Metal decoration is a well-accepted technique in phase contrast microscopy and is known to preserve gross surface features. That it also retains steps on a nearly atomic scale is unexpected and also important, since it provides possible extension of the STM technique to insulator surface studies. On both sides of the step, the surface is flat within 2 Å over distances of 100 and 200 Å, thus *atomically* flat. Any monomolecular steps or clusters on the surface would be detected; however, vacancies in the surface could probably not be seen due to the present lateral resolution.

Temperature changes or relaxation of piezoelectric components may cause a drift which leads to a displacement of successive scans so that the quasi-three-dimensional picture of the surface is somewhat distorted. An example is shown in fig. 2, where the distance between the Y-scans is adjusted at 4.5 Å in the X-direction, and where the displacement varies due to drift. Also, this section of the GaAs facet of 170×130 Å^2 is practically atomically flat with the exception of noise up to 3 Å which may be caused by the sample history and by field-induced desorption effects. Also, local changes of the work function would lead to a fluctuation of the contour lines. After the STM investigation, a Nomarski microphotograph was taken to check whether the earlier published (fig. 3 of ref. [8]) surface features could still be recognized: the rounded growth steps of about 10 Å height and 6 μm mean distance on the otherwise flat surface. The new photograph presented in fig. 3 is practically identical with the earlier published one, and shows, in addition, the damaged areas caused by the STM when the tip hit the surface, either on purpose to mark the area investigated, or accidentally by disturbances.

The areas between the growth steps, 6 μm wide, can be regarded as atomically flat. The achieve-

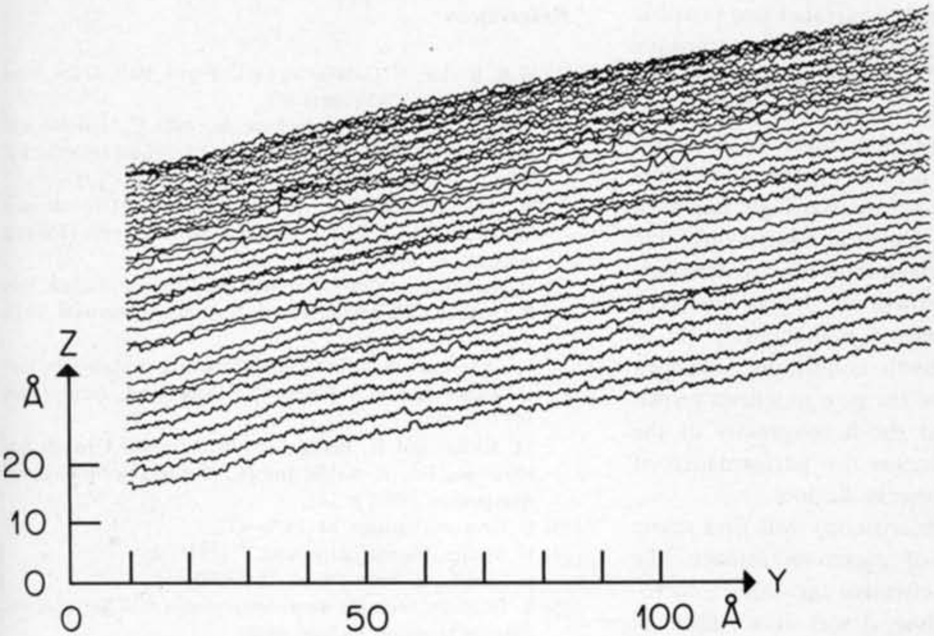

Fig. 2. STM contour lines of LPE-grown GaAs $(\bar{1}\bar{1}\bar{1})$ facet which is scanned in *Y*-direction at ΔX displacements of 4.5 Å. The surface is flat within about 3 Å over an area of 170×130 Å^2.

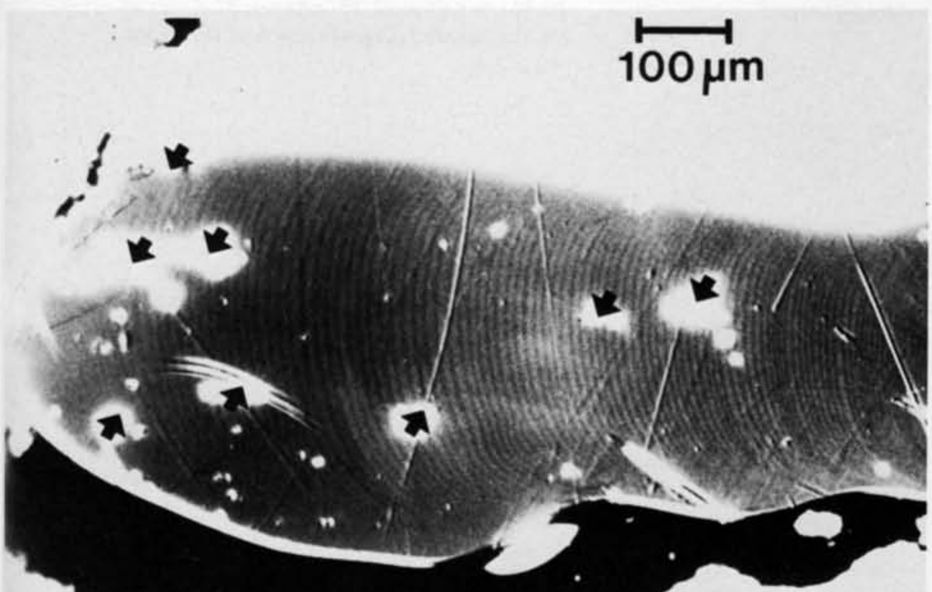

Fig. 3. Nomarski interference contrast micrograph of the GaAs facet after STM investigation. The rounded growth steps have a mean distance of 6 μm and a height (optically) of the order of 10 Å. The arrows show the areas damaged by the tungsten tip.

ment of such nearly step-free surfaces was possible with a sliding-free multilayer LPE technique described earlier [9]. At low supersaturations, the transition from substrates of 0.05° to 0.5° misorientation with tread-riser structures to the facet, with one or a very few growth centers and otherwise rather regular steps about 10 Å high, has been shown reproducibly [8]. On these facets, only one growth mechanism (propagation of microsteps) exists and thus allows growth of doped layers or solid solutions of excellent homogeneity if, in addition, the other growth conditions are optimized. The abruptness of the p–n junctions grown on these flat facets and the homogeneity of the layers are likely to increase the performance of optoelectronic and microwave devices.

Scanning tunneling microscopy will find many applications in fields of materials science like surface physics, surface chemistry (catalysis, corrosion) and metallurgy. Here, it was shown that the STM is a powerful direct tool to investigate crystal-growth surfaces and surface roughness on an atomic scale.

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