SPA-RHEED—A novel method in reflection high-energy electron diffraction with extremely high angular and energy resolution

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A new instrument for spot profile analysis of reflection high-energy electron diffraction (SPA-RHEED) has been developed. The system works either in the conventional mode with a fluorescent screen or in the new high-resolution mode with a channeltron for the registration of the diffraction pattern. The unique properties (a transfer width of 0.2 μm, perfect linearity, high dynamic range, insensitivity to ambient light, low beam current, and energy filtering better than 4 eV) are described in detail. The results show that SPA-RHEED offers new additional applications such as quantitative spot profile analysis for the determination of the surface morphology and lattice constant measurements with an accuracy better than 0.001. © *1995 American Institute of Physics.*

I. INTRODUCTION

Reflection high-energy electron diffraction (RHEED) is a well-established technique for obtaining information on the crystalline structure of surfaces. This technique is based on the diffraction of medium-energy or high-energy electrons (1–100 kV) striking the surface at a small glancing angle. Due to the grazing angle for both incident and scattered beams (forward scattering geometry in RHEED) it is ideally suited for *in situ* monitoring of crystalline growth, since the normal incidence is free for deposition. It has become a standard tool in molecular beam epitaxy (MBE) for the measurement of the growth velocity and the growth mode by use of the RHEED intensity oscillations.[1]

So far, all RHEED measurements are in many respects rather qualitative since linearity, momentum resolution, reproducibility, and the signal-to-noise ratio are limitations for a quantitative analysis of the RHEED pattern.[2] Moreover, dynamic effects and inelastic scattering of electrons are known to be important, although not yet studied in detail for RHEED. Therefore, quantitative data and evaluation concerning the surface morphology are not yet available in the kind used with much success with high-resolution low-energy electron diffraction [spot profile analysis-LEED (SPA-LEED)].[3] RHEED has the additional advantage of a higher transfer width due to the easier focusing and grazing incidence. Therefore an improvement of the equipment presently used is highly desirable.

RHEED patterns are usually observed on a fluorescent screen. This kind of detection enables us to immediately get an overview with quite good resolution. The optical images must be stored and transferred to a computer for data analysis. The dynamic range and the resolution of the whole system is limited by the fluorescent screen and the data acquisition via photodiode or video camera. In addition, the surrounding illumination and lightening by MBE equipment gives a background which may obscure a quantitative analysis.[4] Therefore, it is desirable to avoid the transformation of the electrons to light and then back to an electronic signal. Most important, one has to take into account that the luminescence efficiency is nonlinear, and that linearity is very important for the quantitative analysis of the pattern.

Our aim was to develop a novel RHEED system in order to analyze the spot profiles quantitatively. Therefore we had designed a detection unit similar to SPA-LEED[3] which takes advantage of a channeltron for electron counting, and a set of charged plates for deflecting the RHEED pattern.

II. INSTRUMENTATION

A. Electron gun

The experiments were carried out by a powerful homemade electron gun (Paul-Drude-Institut für Festkörperelektronik, Berlin; formerly the Academy of Science). The electron beam is produced by a standard cathode system with a tungsten filament. Its energy can be varied between 4 and 25 keV. Two pairs of deflection plates bring the beam to the optical axis and one pair deflects the beam to realize angles of incidence up to 10°. The electron beam is formed by an adjustable aperture (0.1, 0.2, or 0.5 mm) and a magnetic lens. Therefore, one can choose the resolution and the intensity by the selection of the aperture. Using the aperture of a diameter of 0.1 mm at 10 keV, one gets a spot diameter on the fluorescent screen of (0.16±0.02) mm (measured by a charge-coupled device camera).

B. Sample manipulation

The sample may be translated linearly in three-dimension, rotated azimuthally, and tilted by ±12°. The tilt axis lies at the surface of the sample in order to vary the angle of incidence without changing the position of the electron beam on the sample. The silicon samples can be heated by direct current or by the heat of radiation up to the melting point. By the use of an e-beam source for silicon different surface morphologies are produced.

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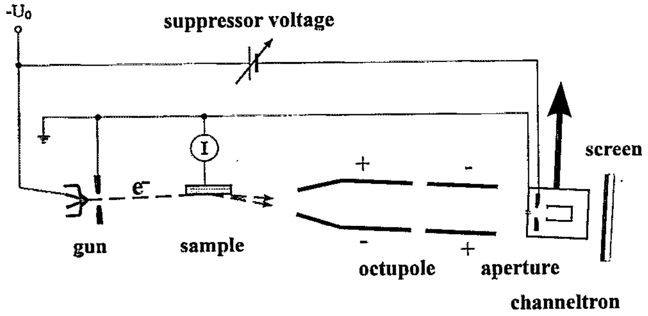

FIG. 1. Schematic setup of the SPA-RHEED system. U_0 determines the primary energy of the electrons.

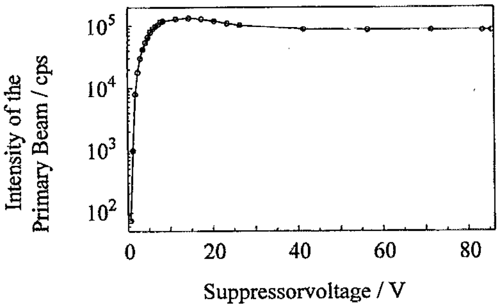

FIG. 3. A characteristic of the electrostatic retarding field (suppressor) in front of the channeltron. The primary energy was (6004±4) eV. The system is stable enough to carry out experiments at the slope.

C. Detection system

The scheme of the whole SPA-RHEED system is given in Fig. 1. A channeltron for electron counting may be shifted into a position in front of the screen. Such a channeltron is characterized by its linearity and its high dynamic range (~6 orders of magnitude). The ultimate resolution of the SPA-RHEED detection unit is given by the diameter of the entrance aperture in front of the channeltron. We have used apertures with diameters of 50 and 100 μm. Between this aperture and the channeltron another aperture with a diameter of 2 mm is placed as a suppressor, so that the channeltron unit may be operated as a retarding field analyzer. The RHEED pattern is scanned over the entrance aperture by means of a set of deflection plates configured as an octupole. The octupole is controlled by a computer which gives a 16 bit signal to a high voltage amplifier. This amplifier supplies the plates with voltages up to ±3500 V. The octupole consists of two parts, each part includes eight electrostatic deflection plates. Due to this arrangement, any electron with diffraction angles up to about 16° pass through the entrance aperture at normal incidence, when the appropriate deflection voltages are applied.

The image of the diffraction pattern is displayed on the screen of the computer using the measured electron intensity and both deflection voltages (x and y direction). By adaptation of the SPA-LEED software package (as available commercially from Omicron Vakuumphysik, D-65232 Taunusstein, Germany), all possibilities concerning data acquisition and treatment of the diffraction pattern are also available for RHEED.

The detection unit is designed for a CF 100 flange to be compatible with commercial RHEED systems.

III. PERFORMANCE

A. Dynamic range and linearity

To illustrate the high dynamic range of the channeltron, Fig. 2 shows a typical scan perpendicular to the shadow edge through the specular beam. The counting rate (intensity) is lower than 10 counts per second (cps) between the primary beam on the left-hand side and the shadow edge, whereas the intensity of the specular beam is higher than 10^5 cps. Counting rates of more than 10^6 cps are possible, and by increasing the measuring time to 12 h, rates as low as 10^{-2} cps can be obtained. To avoid any nonlinear behavior of the detection unit we have used a dynamic range of four or five orders of magnitude. By variation of the beam current we have veri-

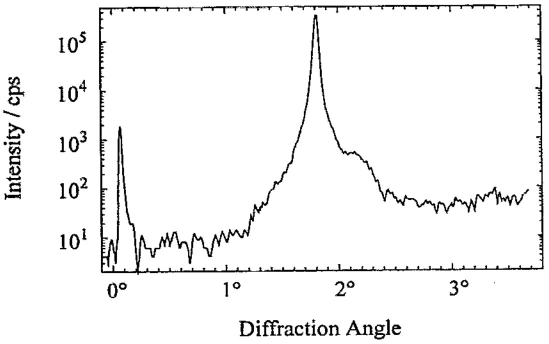

FIG. 2. Presentation of the high dynamic range of a channeltron by a typical SPA-RHEED scan perpendicular to the shadow edge. The scan consists of 500 pixels and was obtained in about 90 s. It covers a dynamic range of five orders of magnitude.

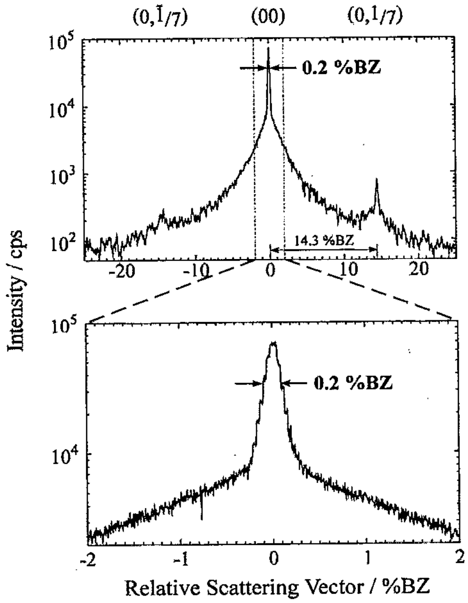

FIG. 4. The angular resolution of the SPA-RHEED system. The logarithmic plot shows a spot profile through the specular beam parallel to the shadow edge. [Si(111)-7×7; [1̄21]-azimuth, primary energy: (4643±4) eV, ΔE=4.5 eV; angle of incidence 2.6°]. The FWHM of 0.2% BZ corresponds to 0.1 mrad=0.005° and to a transfer width of 2000 Å, respectively.

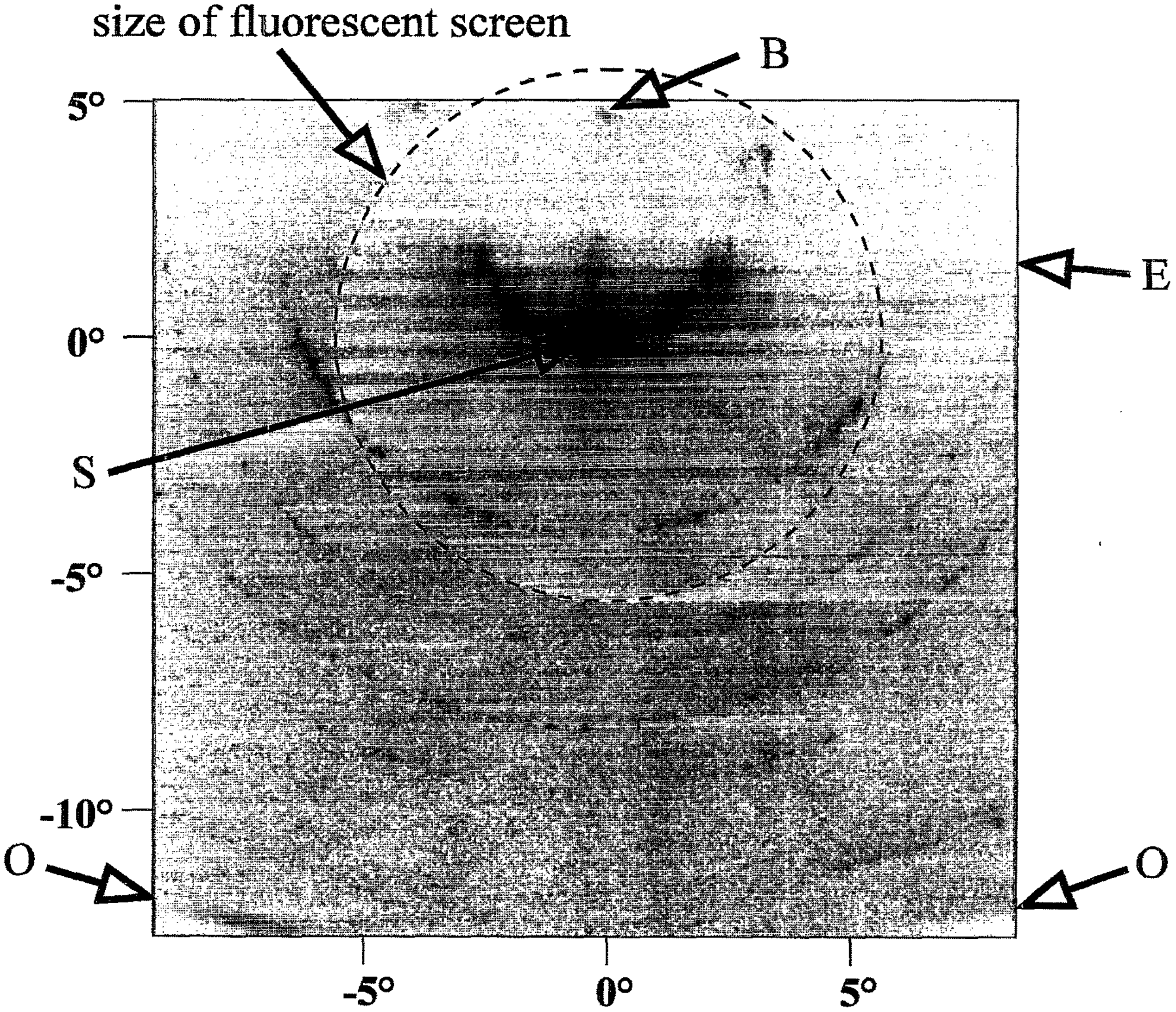

FIG. 5. The scanning range of the SPA-RHEED system. The pattern of Si(111)-7×7 consisting of 400×400 pixel are obtained in the [110]-azimuth; primary energy: (6000±4) eV, $\Delta E=66$ eV, and $\alpha=2.46°$. The time for this measurement corresponds to less than 20 min. The dashed cycle shows the size of our fluorescent screen. B—through beam, S—specular beam, O—limits given by the octupole, E—shadow edge.

fied that the detection unit works without any nonlinearity at counting rates up to more than several 10^5 cps. It should be mentioned that the dynamic range of the best fluorescent screens is not higher than four orders of magnitude.[5]

In the lower part of Fig. 4, one can see discrete steps in the intensity. One step corresponds to 54 mV due to the resolution of the 16 bit signal (maximum voltage 3500 V). The noise level is much lower than 10 mV for the whole system![6]

B. Suppressor

Inelastically scattered electrons are very important in RHEED experiments. Although the fluorescent screens suppress electrons with energies up to about 1000 eV, the diffuse background consists of electrons which have undergone energy losses up to several hundred electron volts.[4] A grid in front of the fluorescent screen cannot provide sufficient resolution to remove plasmon scattered electrons.[7] Using a retarding field analyzer in front of the channeltron, all electrons with losses (ΔE) of more than 4 eV can be suppressed (Fig. 3). Moreover, the instrument is stable enough to carry out measurements at a reduced intensity level ($\Delta E\sim1$ eV). Therefore, with the present SPA-RHEED, the plasmon losses can be suppressed and/or analyzed.[8,9]

C. Angular resolution

A very important feature of a diffraction method is the angular resolution. There are different definitions for the resolution. We have determined the full width at half-maximum (FWHM) of the specular beam. Figure 4 shows two typical RHEED scans parallel to the shadow edge through the specular beam. We have reached a resolution of 0.2% Brillouin zone (%BZ) which corresponds to 0.1 mrad. That means even in the direction parallel to the shadow edge (low resolution) mean terrace sizes of 2000 Å can be detected. Perpendicular to the shadow edge, this value must be divided by sin α (α—angle of incidence),[10] and mean terrace sizes in the micrometer region are resolved without any difficulty. In comparison with the best RHEED and LEED systems, the resolution of SPA-RHEED is at least one order of magnitude higher.[5,11,12]

D. Scanning range

The scanning range depends on the size of the fluorescent screen and on its distance from the sample. Typical values of the scanning range of RHEED systems at MBE chambers are ±5°. In the case of SPA-RHEED the scanning range depends on the distance of the sample and the octupole as well as on the diameter of the octupole. For a distance between sample and octupole of 40 mm, and with an octupole diameter of 90 mm, we get a scanning range of about ±10° (cf. Fig. 5).

IV. DISCUSSION

The SPA-RHEED system stands alone due to its unrivaled properties. The angular resolution of 0.1 mrad is at least one order of magnitude better than any value reported in the literature. This high resolution can be improved even further. Our measurements were carried out at beam currents which are reduced by about two orders of magnitude compared with currents needed for a bright pattern on the fluorescent screen. By the choice of smaller entrance apertures in front of the channeltron and by the use of typical beam currents, the resolution should be improved by one order of magnitude. Values of 10^{-5} rad seem possible. Therefore, lattice constants measurements are comparable with x-ray diffraction in terms of accuracy, however electron diffraction is much more surface sensitive.

The energy filtering of the SPA-RHEED system offers for the first time the combination of high angular and energy resolution. Electrons undergoing plasmon losses can be suppressed. The influence of plasmon scattering to the spot profiles is observed and described quantitatively.[8] By analysis of the inelastically scattered electrons, the kinds of atoms and their stoichiometry at the surface can be determined.[13]

Besides the energy filtering, the linearity, reproducibility, and the dynamic range of the registration unit is very important for the spot profile analysis. Due to the extremely high resolution of the SPA-RHEED system one can resolve distances up to several micrometers. This value is not attainable by high resolution LEED.

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