A simple method for the determination of the angle of incidence for low-energy electrons
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Due to the small elastic mean free path of 10–20 Å, low-energy electrons with kinetic energies below 30 eV are very sensitive to the structure of the surface of single crystals. Low-energy electrons are used to study the electronic structure in photoemission, two photon photoemission, inverse photoemission, and total current spectroscopy or to determine the geometric structure in very low-energy electron diffraction. For all these methods it is very important to determine the angle of the low-energy electrons relative to the sample surface. In electron spectroscopies the usual way of doing this is to measure the dispersion of bulk or surface states. For measurements perpendicular to a mirror plane of the crystal extrema are observed in the dispersion at the center of the surface Brillouin zone \( \Gamma \), that means for normal incidence. Mapping out dispersions is quite a time consuming procedure, because spectra have to be taken for many angles of incidence. In inverse photoemission Royer and Smith used the appearance of a surface state on Cu(111) to calibrate normal incidence conditions of the electron beam. This surface state is 0.4 eV below the Fermi energy at \( \Gamma \) and disperses to higher energies away from the center of the Brillouin zone. They measured the intensity at the Fermi energy as a function of the angle of incidence of the electron beam relative to the surface normal, which showed a strong increase 7.5° off normal where the surface state band crosses the Fermi level. This kind of measurement can also be applied to other transitions at other energies. The described procedure yields curves which are approximately symmetric around \( \Gamma \) which allows the determination of normal incidence of the electron beam. Asymmetries due to the angular distribution of the intensity of the inverse photoemission transitions, which follow partially a squared sine function of the photon takeoff angle relative to the dipole orientation of the transition may complicate the procedure considerably. In addition the data are modified by the transmission probability of the photons through the solid-vacuum interface, qualitatively following the classical Fresnel formulas.

A very fast and simple method to determine the angle of incidence for low-energy electrons without resorting to radiation consists of measuring simply the sample current from the electron gun under consideration. We measured the sample current for a fixed kinetic energy of the electrons as a function of angle of incidence. Changes in the reflectivity of the electrons produce maxima and minima in the angular scans as known from low-energy electron diffraction (LEED) or total current spectroscopy. They are a consequence of the band structure, because the more free-electron like a band is the higher is the coupling probability of the incoming electron to this band. Especially in band gaps at low energies the reflectivity can reach values close to one. The structures seen in the angular scans must be symmetric with respect to the surface normal for scans perpendicular to a mirror plane of the crystal. The sensitivity of this method is greatly enhanced by the measurement of the first derivative of the sample current with respect to the electron energy. This is done by modulating the acceleration voltage of the electrons and measuring the sample current with lock-in technique (Fig. 1). The first derivative of the sample current is shown in Fig. 2 as a function of the incidence angle \( \Theta \) of the electron beam measured relative to the surface normal. The measurements were taken in the \( \Gamma \)XWK mirror plane of a Cu(100) crystal which is perpendicular to another \( \Gamma \)XWK mirror plane. The angle of incidence was varied by rotating the electron gun around the sample. The data show clearly the symmetry with respect to normal incidence as expected for an angular variation normal to a mirror plane of the crystal. Note that the extrema are at the same angle for both kinetic energies proving the proper compensation of the am-

![Fig. 1. Electronic circuit used for our measurements. The last aperture of the electron gun is grounded to ensure a field-free region between the electron gun and the sample. By modulating the acceleration voltage of the electrons and measuring the sample current with lock-in technique the first derivative of the sample current can be measured as a function of the angle of incidence \( \Theta \) of the electrons relative to the surface normal.](image-url)
bient magnetic fields and the absence of stray electric fields. Identical results were obtained by rotating the sample leaving the electron gun fixed. This confirms in addition to the absence of disturbing fields the proper calibration of the rotary motions and, consequently, the angle of incidence scale. From the experimental data we can immediately read off the normal incidence with an accuracy of \( \pm 0.5^\circ \). The main advantage of the described procedure is the ease and speed of the measurements, which take only a couple of minutes. It is, therefore, possible to take data for many energies or many positions of the electron gun.\(^7\)

Finally, we would like to point out that the procedure can be extended to determine the azimuthal orientation of the sample, by measuring the sample current or its energy derivative as a function of the azimuthal angle. For off-normal incidence, extrema should be observed in the mirror planes of the crystal.\(^7\)


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**Probe position controller for plasma parameter measurement in vacuum**

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A probe controller capable of determining both the axial and radial positions of a probe tip to better than 1 mm is described. This controller has an axial span of nearly 40 cm, and a radial span of better than 8 cm. The probe controller system incorporates the electrical feedthroughs for the probe bases, which accept a variety of probe tips. The carriage system is low in profile, so little compromise of experimental volume has resulted from its installation. Our vacuum base pressure, which is approximately 10\(^{-1}\) Torr, has not been affected by either installation or use of this system. Graphs displaying axial and radial plasma profiles taken with the controller are presented.

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**I. INTRODUCTION**

In an experimental program to study the nonlinear waves in plasmas, we insert probes through a vacuum interface into the plasma to view the dynamics of the electron and ion components. Viewing the plasma with a single probe from a variety of positions, or comparing the views from different probes, yields valuable information about wave fronts, potential structures, or any phenomenon that has spatial structure comparable to probe dimensions or spatial separation. The accurate characterization of these structures demands the ability to position the probes on a spatial scale that is small compared to that of the structure under study. In our experimental program, we need the ability to characterize