

# Primary Electron Scattering in Co/Cu(110) Measured by Elastic and Loss Electrons

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Elastically backscattered electrons and electron energy losses were measured for the Co/Cu(110) system at different incidence angles of the primary electron beam to obtain the directional elastic peak electron spectroscopy and directional electron energy loss spectroscopy profiles. The measurements were performed for clean and covered Cu(110) by equivalent quantities of 3 ML and 5 ML of Co. The directional elastic peak electron spectroscopy profiles show a similar distribution of intensity maxima for Cu(110) and Co/Cu(110), which indicates the epitaxial growth of Co layers. The chemical sensitive signal of electron energy losses (Cu and Co  $3p_{3/2}$ ) recorded as a function of the incidence angle of primaries is characterized by modulations which reflect the order within the first few atomic layers of the investigated sample. Therefore, in the case of directional electron energy loss spectroscopy both the chemical and structural information is obtained.

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## 1. Introduction

The chemical and structural information of films grown on well ordered surfaces can be obtained by using experimental methods which utilize the interaction between incidence electrons and solid state atoms. Primary electrons striking the sample undergo elastic and inelastic events. The inelastic scattering is associated with e.g. the hole creation and leads to the loss of the initial electron energy which depends on the kind of atoms in the solid. Therefore the recording of inelastically scattered electrons gives evidence of the chemical composition of samples by using the electron energy loss spectroscopy (EELS) [1–5]. At sufficiently high energies of primaries the inelastic scattering process leads to the Auger electron emission. In this way the Auger electron spectroscopy (AES) [6–8] is a standard tool for the chemical characterization of the investigated solid state surfaces. Depending on the electron energy the elastic events on the atomic potential result in either diffraction or the forward focusing effect [9]. Therefore, the identification of the long range order by using the low energy electron diffraction (LEED) [10] and of the short range order with the use of X-ray photoelectron diffraction (XPD) [11] is possible.

In this work we use the directional elastic peak electron spectroscopy (DEPES) [12] and the directional electron energy loss spectroscopy (DEELS) [13–15] to reveal the crystalline order within the first few atomic layers of the Co/Cu(110) adsorption system. The measurement of elastically backscattered electrons and electron energy losses as a function of the incidence angle of the primary

electron beam showed the usefulness of these experimental methods in investigating the crystalline structure of the Co/Cu(111) system [15]. Both techniques are time reversals of XPD [16], although no photons are involved in the emission process of electrons. Therefore, the characterization of Co layers formed on the Cu(110) surface with the use of the above mentioned techniques seems to be desirable. Different emission processes associated with elastically backscattered and loss electrons are discussed in this paper.

## 2. Experimental

As was already presented in papers [12, 17] in DEPES the signal associated with elastically backscattered electrons is recorded in the normal mode  $N(E)$  as a function of the incidence angle of primaries by using a retarding field analyser (RFA). The independent rotation of the sample around two mutually perpendicular axes, one lying in the sample surface and the other associated with the surface normal, enables a change of the polar and azimuthal angle, respectively. Therefore, the measurement of the elastic peak height as a function of the polar angle  $\theta$  (DEPES profiles) can be repeated for different azimuthal angles  $\phi$ . In the case of DEELS the signal associated with electron energy losses is recorded in the differential mode  $dN(E)/dE$  as a function of the incidence angle. The measurement of electron energy losses requires a significant enhancement of the signal, which is achieved by an increase of the modulation voltage  $U$  of the second and third grid of a four-grid RFA analyser. In the case of DEPES and DEELS the values of  $U = 1$  V and 9 V were chosen, respectively. The intensity of elastically backscattered electrons was measured continuously as a function of the incidence angle of primaries giving a DEPES profile. In order to obtain DEELS profiles the height of a loss peak was determined from the secondary

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emission spectra recorded within an appropriate energy window at different incidence angles. All measurements and the adsorption of Co were performed at room temperature.

### 3. Results and discussion

The structural investigations were performed for two Co coverages, 3 ML and 5 ML. In view of the fact that the surface energetic [18] for this adsorption system causes the formation of subsequent layers before the complete covering of the substrate, which was revealed by scanning tunnelling microscopy (STM) [19] and AES [20], the above coverages correspond to the equivalent quantities of the adsorbate. The results of DEPEs investigations for clean and covered Cu(110) at  $E_p = 1.5$  keV along the Cu $\bar{1}10$  azimuth are presented in Fig. 1. Experimental DEPEs profiles for Co/Cu(110) reveal the intensity maxima [100], [110], and [010] characteristic of the clean substrate. The distribution of signal enhancements for the Co adsorbate and for the clean Cu(110) surface was found to be similar also along the Cu[100] azimuth (Fig. 2). The results obtained for both azimuths show that Co layers reflect the crystalline structure of the substrate.

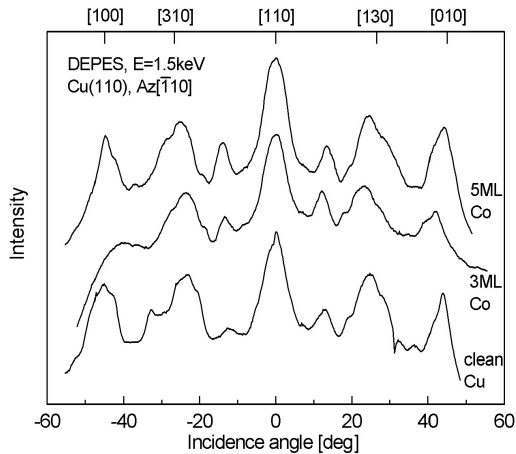


Fig. 1. Experimental DEPEs profiles for clean Cu(110) and equivalent quantities of 3 ML and 5 ML of Co on Cu(110) obtained at  $E_p = 1.5$  keV along the Cu $\bar{1}10$  azimuth.

Cu and Co atoms exhibit more or less similar scattering properties [15], therefore the recorded elastically backscattered electrons do not assure the chemical sensitivity of DEPEs. The structural and chemical information can be simultaneously obtained by recording the directional Auger electron spectroscopy (DAES) profiles [12]. In this method the Auger peak is measured as a function of the incidence angle of the primary electron beam. The direct comparison of the DEPEs and DAES profiles, the latter measured for low and high energetic Auger transitions, recorded at the same primary beam energy  $E_p$  confirms that the angular distribution of

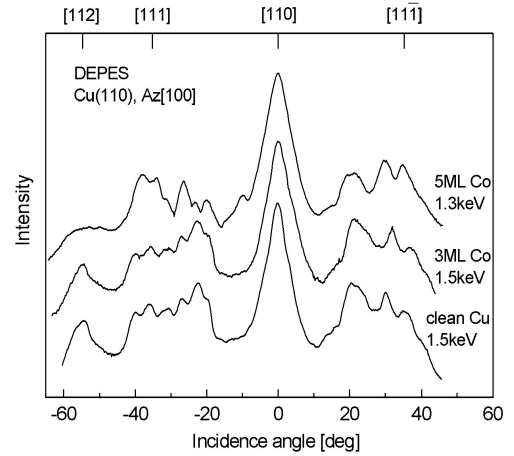


Fig. 2. The same as in Fig. 1 but along the Cu[100] azimuth. Profiles for clean Cu(110) and 3 ML of Co were recorded at  $E_p = 1.5$  keV. The profile for 5 ML of Co was obtained at  $E_p = 1.3$  keV.

emitted electrons does not influence the recorded signal [21, 22]. This signal is mainly affected by the scattering effects of the primary electrons striking the crystalline sample. This is assured by the use of a large acceptance angle collector ( $110^\circ$ ), which integrates the distribution of scattered outgoing electrons over a large solid angle. The applied theoretical approaches, which concern the single [16, 22] and multiple [23] scattering of primaries, confirm the dependence of the signal on the incidence direction. In these formalisms the electron wave field in a solid is calculated by taking into account a quantum mechanical nature of the scattering process of electrons on the atomic potential. The consideration of the real experimental geometry in these formalisms associated with the sample rotation with respect to the axial electron gun and a limited acceptance angle of RFA leads to good correspondence between theoretical and experimental data [16, 21–23].

Another way to obtain chemical information is the recording of electron energy losses which result from the inelastic scattering of primary electrons on solid state atoms. In view of the fact that the recorded signal is considerably lower than the Auger signal the appropriate enhancement of the measured current is required. In the investigations performed by Mróz [13] and Swatek [14] the dependence of the signal associated with the electron energy losses on the incidence angle was found to be sensitive to the crystal structure. This dependence was later confirmed for the Co/Cu(111) adsorption system [15]. In Fig. 3 the DEELS profiles are shown for clean and covered Cu(110) along the Cu $\bar{1}10$  azimuth at  $E_p = 0.6$  keV. The signal corresponds to  $3p_{3/2}$  electron excitations in Cu and Co. In spite of the large noise in the recorded signal the enhancement of the recorded intensities is noticed at incidence angles corresponding to the close packed rows of atoms [100], [110], and [010] within Cu and Co layers.

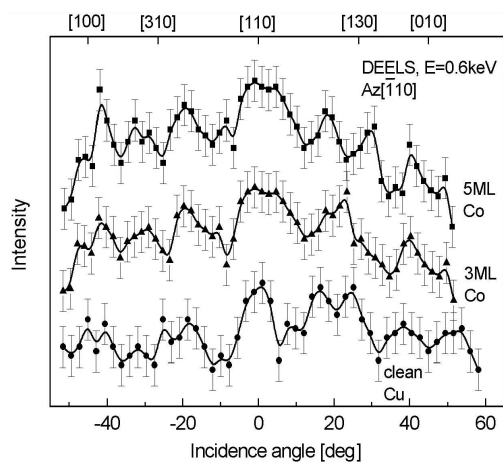


Fig. 3. Experimental DEELS profiles for clean (Cu  $3p_{3/2}$ ) and covered (Co  $3p_{3/2}$ ) substrate by equivalent quantities of 3 ML and 5 ML of Co at  $E_p = 0.6$  keV along the Cu  $\bar{1}10$  azimuth. Solid line is shown to keep an eye on the signal modulation.

This result and the similarity of the DEPEs, DAES, and DEELS profiles found in [15] suggest that the intensity maxima observed in the DEELS profiles originate from the scattering events of primaries.

We calculated scattering factors for Cu and Co as a function of the scattering angle by using the MS program [23], which involves phase shifts obtained in a muffin-tin approach [10] similarly as in calculations of XPD distributions [16]. The results of calculations for Cu presented in Fig. 4 show that at energies used in the experiment  $E_p = 0.6$  keV and 1.5 keV the forward scattering of primaries is significant. The values of the scattering factors  $f(\theta_s, d)$  [23–25], where  $\theta_s$  is the scattering angle and  $d$  is the distance from the scatterer equal to  $2.5 \text{ \AA}$  corresponding to the nearest neighbor, are dominant at  $\theta_s = 0^\circ$ . At lower energies the contribution of backscattered electrons ( $\theta_s = 180^\circ$ ) becomes noticeable, although the  $f(\theta_s, d)$  values are significantly reduced in comparison with the values at  $\theta_s = 0^\circ$ . A similar dependence of the  $f(\theta_s, d)$  factor was obtained for the Co atom as a scatterer. The scattering factors and phases for Cu and Co have been presented in the work [15]. The amplitude of the scattered wave in a solid strongly depends on  $f(\theta_s, d)$  and the attenuation factor [26]. As a consequence the amplitude of the electron wave localized on an emitter is governed by the incidence direction of the primary plane wave. The parallel setting of the electron gun axis and the close packed atomic row results in an increase of the recorded signal (Figs. 1–3). The DEELS results obtained for the Cu[100] azimuth (not shown here) reveal also the main intensity enhancement associated with the [110] direction and reduction of intensities along high index directions.

The emission process is different in the case of DEELS in comparison with DEPEs and DAES. In DEELS the elastic scattering before loss and the loss before elastic

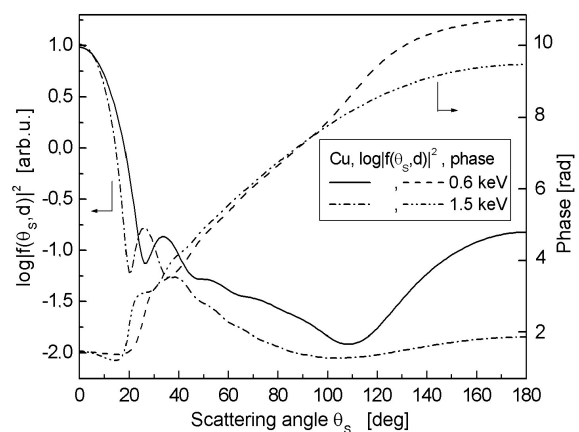


Fig. 4.  $\log |f(\theta_s, d)|^2$  and phase calculated for Cu at the distance from the scatterer  $d = 2.5 \text{ \AA}$  and  $E_p = 0.6$  and 1.5 keV as a function of the scattering angle  $\theta_s$ .

scattering events should be taken into account. The former process leads to the forward focusing of primaries along the incidence direction and then to the loss of their initial energy. Most of inelastically scattered electrons propagate in the forward direction [4]. As a consequence the reflection of electrons towards the RFA analyzer must be accompanied by an additional elastic scattering. Therefore, at least three atomic layers are involved in this process. If the primary beam strikes the sample parallel to the close packed atomic row, an increase of the signal associated with electron energy losses is expected.

In the other emission process the loss of the electron energy before the elastic scattering takes place. The inelastically scattered electrons on atoms in the first layer can be elastically backscattered on atoms in the second layer and then reach an RFA collector giving contribution to the measured signal. The second scenario considers the forward scattering on atoms in the second layer and elastic backscattering in the third layer. Both processes lead to an increase of the recorded intensities.

In the case of DEPEs only elastically backscattered electrons contribute to the measured signal. The Auger signal recorded in DAES is influenced by primary electrons as well as elastically and inelastically backscattered electrons and secondary electrons with a sufficient energy necessary to initiate the Auger process. Thus, in DAES the backscattering factor plays a significant role. In DEELS no secondary and inelastically backscattered electrons influence the measured signal. The emission is governed only by primary and elastically backscattered electrons. In consequence DEELS seems to be a useful tool for investigating the chemical composition and structure of ultrathin films and superficial alloys.

Theoretical DEPEs profiles obtained for the Co/Cu systems by using the MS theory [23] well reflect intensity maxima observed in experimental distributions [20, 27]. Calculated DEPEs data for Cu and Co are very simi-

lar because of comparable scattering factors and inelastic mean free paths [28]. The simulations of DEELS profiles needs however more effort than calculations of DEPES distributions. Such theoretical analysis requires the consideration of different emission mechanisms of electron energy losses, described in this paper, and is still under elaboration. Therefore, in this paper we present only experimental results.

In the incidence electron beam experiments the surface excitations influence to some extent the recorded signal especially in DEELS. These effects become important at grazing incidence angles. The range of incidence angles measured with respect to the surface normal does not exceed 60° in all experiments. Therefore, we expect these effects to play a minor role in the measured signal.

#### 4. Conclusions

The DEPES and DEELS investigations enabled the identification of the crystalline structure of the Co/Cu(110) adsorption system. For 3 ML and 5 ML coverages the Co layers reflect the structure of the substrate. The discussed different emission mechanisms in DEPES, DAES, and DEELS show the usefulness of the latter method in structural investigations. The advantage of DEELS is its chemical sensitivity.

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