Quantum-well states in ultrathin Ag(111) films deposited onto H-passivated Si(111)-(1x1) surfaces

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Ag(111) films were deposited at room temperature onto H-passivated Si(111)-(1x1) substrates, and subsequently annealed at 300 °C. An abrupt non-reactive Ag/Si interface is formed, and very uniform non-strained Ag(111) films of 6-12 monolayers have been grown. Angle resolved photoemission spectroscopy has been used to study the valence band electronic properties of these films. Well-defined Ag sp quantum-well states (QWS) have been observed at discrete energies between 0.5-2eV below the Fermi level, and their dispersions have been measured along the ΓK, ΓM(M′) and ΓL symmetry directions. QWS show a parabolic bidimensional dispersion, with in-plane effective mass of 0.38-0.50m0, along the ΓK and ΓM(M′) directions, whereas no dispersion has been found along the ΓL direction, indicating the low-dimensional electronic character of these states. The binding energy dependence of the QWS as a function of Ag film thickness has been analyzed in the framework of the phase accumulation model. According to this model, a reflectivity of 70% has been estimated for the Ag-sp states at the Ag/H/Si(111)-(1x1) interface.

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I. INTRODUCTION

During the last years, the study of low-dimensional structures has attracted considerable interest because spatial confinement of electrons in thin films results in discrete quantum-well states (QWS). In semiconductor layer systems, these effects are well known, and they have been already used in electronic devices. However, the observation of quantization effects in metallic layers, has been restricted to a few systems. In this respect, thin Ag films have attracted a great interest due to the nearly free-electron characteristics of the sp bands over large regions of the Brillouin zone (BZ). Ag-sp QWS have been widely observed in thin Ag films deposited onto several metallic substrates. In contrast, confinement effects on Ag films deposited onto semiconductor substrates have been only observed in a scarce number of systems. Weak peaks associated to QWS have been observed by Wachs et al. in the photoemission spectra of 5-15 monolayers (ML) Ag films deposited on Si(111)-(7x7) at room temperature (RT). The weakness of the QWS observed by these authors could be associated with the formation of a non-uniform Ag island size distribution, which would wash out the manifestation of quantum size effects in photoemission. These facts suggest that an improvement of Ag deposition conditions and silicon substrate preparation could play a key role for the observation of well-defined QWS in thin Ag films deposited onto silicon substrates. In fact, this has been observed by Neuhold and Horn on a 21ML Ag film deposited at 130 K onto a Si(111)-(7x7) substrate, and subsequently annealed at RT. Such special deposition conditions lead to the formation of more uniform Ag films, where quantum-size effects have been observed by photoemission, although strain induced by film growth was also present in the film. Therefore, it would be desirable from both fundamental and technological point of views, to consider alternative better Si(111) surfaces free of complex reconstruction structures, which could lead to the formation of high-quality non-strained Ag(111) films.

The nucleation and growth mode of thin Ag films deposited onto Si surfaces can be modified by changing the surface free energy of the substrate. This modification can be accomplished by termination of the Si(111) surface by a foreign atom. By this reason, there is a great interest in the formation of high quality artificially H-terminated Si(111)-(1x1) surfaces, by both a wet chemical treatment and an atomic hydrogen-based method. Hydrogenation of the Si(111)-(7x7) surface saturates the dangling bonds, restoring the (1x1) symmetry of bulk silicon. In a recent study on the electronic structure of the H-terminated Si(111)-(1x1) surface, the high quality of such a type of unreconstructed Si surfaces prepared by a wet chemical treatment has been confirmed by angle resolved photoemission spectroscopy (ARPES). Remarkably sharp features have been resolved in the valence band photoemission spectra at the K-point, being attributed to: (i) a surface resonance with a pₓ-pᵧ symmetry, (ii) a surface state identified as a Si-Si backbond state, and (iii) two higher binding-energy H-Si surface states.

The growth mode and structure of thin Ag films deposited onto hydrogen passivated silicon surfaces are substantially different from the observed ones for Si(111)-(7x7) surfaces. When Ag is deposited onto a clean Si(111)-(7x7) surface, the growth proceeds in a quasi-
layer-by-layer mode at RT, and according to Stranski-Krastanov growth mode at 300 °C. Opposite to this, Ag deposition at 300 °C onto the H/Si(111)-(1x1) surface, leads to a quasi-layer-by-layer growth mode. In this case, the formation of islands much thinner and with a narrower size distribution than those on the non-passivated substrate has been observed by impact-collision ion-scattering spectroscopy (ICISS) and scanning electron microscopy (SEM) [3]. In addition, Sumitomo et al. [4] have found that Ag films deposited onto Si(111)-(7x7) substrates at RT have a two-domain Ag(111) islands distribution, whereas those grown on the hydrogen-terminated surface at 300 °C have a single-domain preferred orientation. According to these authors, hydrogen-mediated epitaxy (HME) of single-domain Ag(111) films deposited on Si(111)-(7x7) substrates at 300 °C is observed. It has been suggested that hydrogen at the interface can be partially removed during Ag deposition at high temperatures. If the hydrogen coverage at the interface would decrease below 0.3 ML, an undesired reconstruction of the surface, to a 2D layer of the Ag(111)√3x√3R30° structure plus thicker Ag(111) islands could occur. So, it would be desirable to lower the Ag temperature deposition in order to avoid a significant hydrogen elimination at the interface, and therefore the above-mentioned surface reconstruction.

Ag deposition at RT onto hydrogen-terminated Si(111) surfaces has been only studied by scanning tunneling microscopy (STM). It was observed an increase of the average size of the Ag islands upon increasing the substrate temperature from RT to 300 °C. On the contrary, the Ag(111) island density decreases, and therefore RT deposition leads to even more uniform and compact Ag films than those deposited at higher temperatures. Unfortunately, in the literature there is a lack of information from structural techniques about the single or two-domain preferred orientation of thin Ag films deposited on hydrogen-terminated Si substrates at RT. Recently, the above-mentioned subject has been addressed studying the Fermi surface (FS) of 6ML Ag films deposited onto H-passivated Si(111)-(1x1) surfaces at RT, and subsequently annealed at 300 °C [5]. This study has shown that the measured FS reflects a sixfold symmetry rather than the threefold symmetry expected for a Ag(111) single crystal. This behavior has confirmed the fact that these Ag films are composed by two domains rotated 60°, being the first evidence of a two-domain preferred orientation of the Ag(111) films deposited at RT onto H-terminated Si(111)-(1x1) surfaces.

In this work, thin Ag(111) films have been deposited in ultra-high-vacuum (UHV) at room temperature (RT) onto H-passivated Si(111)-(1x1) substrates, and subsequently annealed at 300 °C to enhance the film uniformity. In such a way, an abrupt non-reactive Ag/Si interface is formed, and high-quality non-strained thin Ag(111) films of 6-12ML have been obtained. The quality of the silver films has been probed by ARPES. Well-defined Ag sp QWS have been observed at discrete energies between 0.5-2eV below the Fermi level ($E_F$), and their energy dispersions have been measured along the $\Gamma K$, $\Gamma M(M')$ and $\Gamma L$ symmetry directions. QWS show a parabolic dispersion, with in-plane effective mass of 0.38-0.50$m_0$, along the $\Gamma K$ and $\Gamma M(M')$ symmetry directions, whereas no dispersion has been found along the $\Gamma L$ direction, supporting the two-dimensional electronic character of these states. On the other hand, the binding energy dependence of the QWS as a function of Ag film thickness has been analyzed in the framework of the phase accumulation model. A good agreement between experimental data and the above-mentioned model is obtained for the Ag/H/Si(111)-(1x1) system.

II. EXPERIMENTAL DETAILS

The experiments were performed at LURE (Orsay, France) using the French-Spanish (PES2) experimental station of the Super-Aco storage ring, described elsewhere. The measurements were carried out in a purpose-built UHV system, with a base pressure of 5x10$^{-11}$ mbar, equipped with an angle resolving 50 mm hemispherical VSW analyzer coupled on a goniometer inside the chamber. The manipulator was mounted in a two-axes goniometer that allows rotation of the sample in: (i) The whole 360° azimuthal angle (φ) and (ii) In the 180° polar emission angle relative to surface normal (θ), with an overall angular resolution of 0.5°. The current incident angle of the light ($\Theta_i$) was 45°. The available energy of light (hν) was between 18 and 150 eV.

The substrates were n-doped Si(111) single crystal, with a nominal resistivity of 100 Ωcm. It was prepared ex situ using a wet chemical treatment that results in a passivated H/Si(111)-(1x1) surface. After introducing the substrate in the analysis chamber, the quality of the surface was checked out through the sharpness of the features appearing in the valence band photoemission spectrum at $\Gamma$-point, which are attributed to intrinsic H-Si surface states. Ag was evaporated onto the surface at RT. The rate of evaporation, 0.06 ML/min, was determined by using a quartz microbalance. In these conditions, Ag films of thickness ranging from 6 to 12 ML were deposited onto H/Si(111)-(1x1) surfaces at RT, and subsequently annealed at 300 °C to enhance the film uniformity.

III. RESULTS AND DISCUSSION

Normal and off-normal valence band (VB) photoemission spectra, after background subtraction, of 6-12ML Ag films deposited at RT onto H-terminated Si(111)-(1x1) substrates and subsequently annealed at 300 °C, are presented in order to obtain the Ag sp-band dispersion along the $\Gamma L$, $\Gamma K$ and $\Gamma M(M')$ symmetry directions. Fig. 1 shows the evolution of the normal emis-
ion VB spectra measured with $h\nu=32$eV as a function of Ag thickness. The intense and sharp peak observed at 0.1eV below $E_F$ is the surface state (SS) in the band gap along the direction of the Ag(111) crystal. The sharpness of this peak reflects the good crystallinity and orientation of the Ag film. It should be pointed out that the sharpness observed for this peak is comparable to the observed one for Ag films deposited onto highly oriented pyrolytic graphite, HOPG(0001), where a very narrow height distribution Ag islands has been observed.\textsuperscript{4} Neuhold and Horn\textsuperscript{14} have attributed the depopulation of the Ag SS to the presence of tensile strain induced by film growth in a 21ML Ag film on Si(111)-(7x7). Comparison of our results with the works of Wachs et al.\textsuperscript{13} and Neuhold and Horn\textsuperscript{14} suggests an improvement of the quality of the silver films, as a consequence of the ideally H-terminated Si(111) substrate used in this work. As a consequence, high-quality non-strained Ag films can be successfully prepared onto H-passivated Si(111)-(1x1) surfaces at RT, with a subsequent annealing. Alternative techniques for Ag deposition based on the cooling of the substrate to 130 K and subsequent annealing at RT, lead also to the formation of high-quality Ag films where manifestation of quantum-size effects in photoemission has been observed.\textsuperscript{2} However, effects associated to the strain cannot be avoided, and it should be taken into account to describe the electronic properties of such Ag thin films.

Three series of well-resolved intense Ag sp QWS, characterized by the quantum number $\nu=1$ to 3, can be observed at discrete energies between 0.5-2eV below the Fermi level in Fig. 1. The evolution of the QWS energies as a function of Ag thickness for the different series observed ($\nu=1$, 2 and 3) will be analyzed later in the backdrop of the phase accumulation model, (PAM).\textsuperscript{5} The quantum number $\nu$ is defined as, $\nu = m - n$, where $m$ is the number of Ag MLs, and $n$ is the number of antinodes in the probability density. Ag sp QWS of similar quality have also been observed by Neuhold and Horn\textsuperscript{14} in a 21ML Ag film on Si(111)-(7x7), deposited at 130 K and subsequently annealed at RT, suggesting that special Ag deposition conditions, or as shown in this work, Si(111) substrates free of complex surface reconstructions, are necessary in order to observe quantum size effects in Ag films deposited over Si(111) substrates. Therefore, it should be pointed out that the weakness of the QWS peaks observed by Wachs et al.\textsuperscript{13} in the photoemission spectra of 5-15 MLs Ag films deposited at RT onto Si(111)-(7x7) should be associated with the formation of a non-uniform Ag island size distribution, as a consequence of standard deposition at RT. In the lower part of Fig. 1, the sp-band dispersion, $E(k_\perp)$, of bulk Ag along the $\Gamma L$ direction is shown in order to illustrate the physical origin of the QWS peaks observed in the spectra. The above-mentioned dispersion relation $E(k_\perp)$ has been simulated by the two band model given by Eq. (1),\textsuperscript{2}

$$E(k_\perp) = E_0 - A(k_{BZ} - k_\perp)^2 + U - \sqrt{4A^2B(k_{BZ} - k_\perp)^2 + U^2}$$  \hspace{1cm} (1)$$

where $A = h^2/2m^*$, $B = 3\pi^2/a^2$, $a=4.09\text{Å}$ is the silver lattice constant, $U=4.2$eV is the width of the gap at the $L$ symmetry point of Ag(111), $E_0=0.31$eV is the position of the sp-band edge relative to $E_F$, $m^*=0.7m_e$ is the effective mass of the electrons in this band, being $m_e$ the free electron mass, and $k_{BZ}=1.33\text{Å}^{-1}$ is the wave vector at the BZ boundary (the $L$ point in the [111] direction).

Angle-resolved photoemission spectra of the VB measured with $h\nu=32$eV, along the $\Gamma K$ and $\Gamma M(M')$ symmetry directions are presented in Figs. 2 and 3, for 6 and 7ML Ag films, respectively. As a reference, a scheme of the Ag(111) surface reciprocal-lattice unit cell is shown in the figures. It should be pointed out, that $M$ and $M'$ points of the surface BZ overlap because Ag films are composed by two 60° rotated domains.\textsuperscript{2} Dashed lines have been added to show the energy dispersion of the different peaks observed in the spectra. These peaks are the QWS denoted by $\nu=1$ and $\nu=2$ in Fig. 1, and the feature associated with the Ag(111) surface state. The insets of figs. 2 and 3 show the band diagram extracted from the dispersion of these features. Solid lines are parabolic fits to Eq. (2), that are expected to be a good approximation for small parallel wave vector, $k_\parallel$, values.\textsuperscript{2}

$$E_\nu(k_\parallel) = E_\nu(k_\parallel = 0) + h^2k_\parallel^2/2m^*_\parallel$$  \hspace{1cm} (2)$$

In Eq. (2), $E_\nu(k_\parallel = 0)$ and the in-plane effective mass, $m^*_\parallel$, are fitting parameters.

In agreement with a previous work\textsuperscript{2} two sp Ag derived surface states, $SS1$ and $SS2$, at binding energies of $\sim 0.1$ and 0.32eV, respectively, are found in the gap along the $\Gamma L$ direction of the Ag(111) films. The existence of two different surface states with the same origin was attributed to the inhomogeneous presence of hydrogen at the interface, due to the fact that annealing process partially removes hydrogen, and therefore, a downshift of the Ag surface state is produced in regions where hydrogen still remains at the interface. It should be noted, that for Ag film thicknesses $\geq 6$ML, the $SS2$ feature appears as an asymmetry of the more intense $SS1$ peak in normal emission spectra. However, $SS2$ peak becomes clearly resolved in off-normal emission spectra of Figs. 2 and 3, as a consequence of the Fermi level crossing of the $SS1$ state.

Surface states and QWS show a parabolic in-plane dispersion as can be observed in the insets of figs. 2 and 3. The QWS in-plane effective mass, $m^*_\parallel$, has been obtained from the fit of experimental data to Eq. (2), giving values between 0.38-0.50$m_e$. These values are in good agreement with the reported ones in the literature for silver films on Cu(111) substrates, and are almost the same as the effective mass for the Ag sp valence band derived from a band structure calculation.\textsuperscript{4} Moreover, it has been also observed the linear increase of the in-plane effective mass with the binding energy found for Mueller et al.\textsuperscript{3} for the Ag/Cu(111) quantum-well system.\textsuperscript{3}
The evolution of the normal emission BV spectra as a function of $h\nu$ for a 7ML Ag(111) film is presented in Fig. 4. As can be observed, a negligible dispersion is found for the QWS along the ΓL symmetry direction, as a consequence of the quantization of the perpendicular wave vector component, $k_\perp$, due to the finite and homogeneous thickness of the film. The non-dispersive behavior along the ΓL direction, and the parabolic in-plane dispersion along the ΓM and ΓM(M') symmetry directions of the QWS and surface states, indicate the two-dimensional electronic character of these states.

Observation of confinement effects in the Ag/H/Si(111)-(1x1) system, requires either the presence of a relative gap in the Si(111) substrate, or the presence of a so-called symmetry or hybridization gap, in order to avoid the coupling of Ag-sp states with Si(111) sp-states of similar symmetry. Well-defined QWS have been observed in this work for energies between 0.5 and 2eV below $E_F$. Neuhof and Horn have also observed similar quality QWS up to an energy of 3eV below $E_F$. So, the above-mentioned requirements should be fulfilled for hydrogen passivated and non-passivated silicon substrates. It should be pointed out that according to the calculated valence band structure, the gap at the Γ point in the [111] direction of the silicon substrate extends up to ~1eV below $E_F$, so the observation of QWS for binding energies above 1eV, should be explained by the lack of coupling between the Ag-sp states and the Si(111) bulk states. The role of the presence of hydrogen at the Ag/Si(111) interface should be also taken into account. It should act as a barrier, that would enhance the inhibition of the above-mentioned coupling, as it has been observed in the 15ML Ag + xML Au + Ag(111) quantum-well system, upon increasing the Au interlayer thickness from $x=0$ to 3ML.

In order to further analyze the dependence of the QWS energies with the Ag film thickness, the binding energies of the QWS observed in Fig. 1 are plotted (solid symbols) as a function of the Ag film thickness in Fig. 5. In this figure, data corresponding to 5-13ML Ag films deposited onto Si(111)-7x7 at RT have been also plotted for comparison (open symbols). According to the phase accumulation model, the energy position of the QWS is given by Eq. (3),

$$2k_\perp(E)d + \Phi_C(E) + \Phi_B(E) = 2\nu\pi$$

where $k_\perp(E)$ is the electron wave-vector component normal to the surface, $d$ is the Ag film thickness, $\nu$ is the quantum number previously defined, and $\Phi_C(E)$ and $\Phi_B(E)$ are the phase shifts upon reflection of the electron wave-function at the film/substrate and film/vacuum interfaces, respectively. The above-mentioned model considers that QWS are electron waves trapped inside the Ag film between the barriers at the Ag/Si(111) and Ag/vacuum interfaces. Upon reflection of the Ag-sp electrons at the interfaces, phase changes are introduced, $\Phi_C(E)$ and $\Phi_B(E)$, whereas $k_\perp(E)d$ is the phase change accumulated upon traversing the Ag film. In this way, thin uniform Ag films can be considered as an electron interferometer where the electron undergoes multiple reflections between the interfaces. For a given Ag film thickness, a Ag-sp electron standing wave is expected at a discrete energy in the photoemission spectra, when the total phase change satisfies the condition given by Eq. (3).

In Eq. (3), the dispersion relation $k_\perp(E)$ for Ag(111) in the ΓL direction can be simulated by the two-band model previously defined by Eq. (1). $\Phi_B(E)$ and $\Phi_C(E)$, are described by Eqs. (4) and (5), respectively,

$$\Phi_B(E) = \pi \frac{3.4eV}{E_V - E - 1}$$

$$\Phi_C(E) = -\alpha\pi$$

where $E_V=3.7eV$ is the vacuum level and $\alpha$ is a fitting parameter that can take values between 0 and 1. Eq. (4) is the common empirical approximation used in the literature for $\Phi_B(E)$, whereas $\Phi_C(E)$ has been defined to take values between 0 and $-\pi$. A value of $\alpha=1$ in Eq. (5), would imply a nearly 100% reflectivity at the Ag/substrate interface, as has been proposed for the Ag/fcc-Fe(100) system. For other systems, a different empirical relation based on a step potential approximation for $\Phi_C(E)$ has been proposed, but this does not seem to be valid for the Ag/Si system, where a combination of relative and symmetry gaps should be considered in order to account for the observed confinement effects.

Dashed lines in Fig. 5 represent the calculated thickness dependence of the binding energy of the QWS (with $\nu=1$-3) based on the fit of the experimental data (solid symbols) to the PAM proposed by Eq. (3). The best fit has been obtained for $\alpha=0.7$. This value can be interpreted as a ~ 70% reflectivity of the Ag-sp states at the Ag/H/Si(111) interface. A good agreement between experimental data and calculated lines is obtained, suggesting that the PAM can successfully characterize the QWS observed in the Ag/H/Si(111)-(1x1) system, taken into account that an independent energy approximation for $\Phi_C(E)$ has been used. Obviously, a better agreement could have been obtained if the total phase shift would have been simulated by a third-order polynomial but in this case direct information about the Ag-sp states reflectivity at the interface would have been lost.

Finally, it should be pointed out, that the same model of Eq. (3) applied to data of the Ag/Si(111)-(7x7)
system (open symbols of Fig. 5) gives $\alpha \sim 0$. This would imply a nearly zero reflectivity at the Ag/Si interface, and therefore no QWS should have been observed. In order to account for this result, two additional effects should be taken into account. The influence of induced-film-growth strain in the electronic structure ($E(k)$) of Ag films deposited onto Si(111)-7x7 substrates at RT and the inhibiting electronic-coupling role of the remaining hydrogen at the interface.

IV. SUMMARY AND CONCLUSIONS

Thin Ag(111) films have been deposited in UHV at room temperature onto H-passivated Si(111)-(1x1) substrates, and subsequently annealed at 300 °C to enhance the film uniformity. Deposition onto H-terminated Si(111)-(1x1) unreconstructed surfaces suppresses strain induced by film growth. As a consequence, an abrupt non-reactive Ag/Si interface is formed, and very uniform non-strained Ag(111) films of 6-12ML have been obtained. The quality of the silver films has been probed by ARPES. Well-defined Ag-sp QWS have been observed at discrete energies between 0.5-2eV below the Fermi level, and their energy dispersion have been measured along the $\Gamma K, \Gamma M(M')$ and $\Gamma L$ symmetry directions. QWS show a parabolic dispersion, with in-plane effective mass of 0.38-0.50$m_0$, along the $\Gamma K$ and $\Gamma M(M')$ directions, whereas no dispersion has been found along the $\Gamma L$ direction, supporting the two-dimensional electronic character of these states.

On the other hand, the binding energy dependence of the QWS as a function of Ag film thickness has been analyzed in the framework of the phase accumulation model. A good agreement between experimental data and the above-mentioned model is obtained for the Ag/H/Si(111)-(1x1) system, and a $\sim 70\%$ reflectivity for the Ag-sp states at the Ag film/substrate interface has been derived. Comparison of our results with the scarce works existing in the literature on QWS in the Ag/Si(111) system, suggests that the influence of strain induced by film growth in the electronic structure of Ag films deposited onto Si(111)-7x7 substrates, should be also taken into account in order to accurately describe the electronic properties of those films. In addition, hydrogen at the interface enhances the degree of confinement of electrons in the Ag thin film, acting as a barrier that inhibits the electronic-coupling between Ag and Si sp states at the interface.

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FIG. 1. Normal emission valence band spectra measured with $h\nu=32eV$ for different Ag film thicknesses deposited onto an H-terminated Si(111)-(1x1) substrate at RT, and subsequently annealed at 300 °C. In the bottom, the $sp$-band dispersion, $E(k_\perp)$, of bulk Ag along the $\Gamma L$ direction is shown in order to illustrate the physical origin of the QWS peaks observed in the spectra.

FIG. 2. Angle-resolved photoemission spectra of the VB measured with $h\nu=32eV$ along the $\Gamma K$ symmetry direction for the 6ML Ag film of Fig. 1. As a reference, a scheme of the Ag surface reciprocal-lattice unit cell is given in the figure. The inset shows the band diagram extracted from the dispersion of the features observed in the spectra.

FIG. 3. Angle-resolved photoemission spectra of the VB measured with $h\nu=32eV$ along the $\Gamma M(\Gamma)$ symmetry direction for the 7ML Ag film of Fig. 1. As a reference, a scheme of the Ag surface reciprocal-lattice unit cell is given in the figure. The inset shows the band diagram extracted from the dispersion of the features observed in the spectra.

FIG. 4. Normal emission valence band spectra as a function of the energy of light, $h\nu$, for the 7ML Ag film of Fig. 1.

FIG. 5. QWS binding energies of Fig. 1 as a function of Ag film thickness (solid symbols). For comparison data corresponding to 5-13ML Ag films deposited onto Si(111)-(7x7) at RT, extracted from reference 14, have been also plotted (open symbols). Dashed lines are the calculated thickness dependence of the QWS binding energies according to the phase accumulation model proposed in the text.

FIG. 6. Schematic diagram illustrating the analogy of the multiple-reflection phase accumulation model with an electron interferometer for the Ag/Si(111)-(1x1)-H system. Multiple reflections at the interfaces of Ag-$sp$ electrons are indicated by dashed arrows. Evanescent states outside the Ag films due to interface reflectivities lower than 100%, are indicated by short arrows.
$h\nu = 32\text{ eV}$

$\Gamma$-point

$\theta_{\text{Ag}}$ (ML)

Intensity (arb. units)

Binding energy (eV)

$\nu = 3$

$\nu = 2$

$\nu = 1$

QWS

SS
A g/H/Si(111)-(1x1)

A g/Si(111)-(7x7); Ref.[14]
