Finite size effects in surface states of stepped Cu nanostructures

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Cu nanostructures with finite arrays of monatomic steps are self-assembled by Ag-induced faceting of vicinal Cu(111) surfaces. By varying the amount of Ag in the submonolayer range one can tune the internal step spacing d of Cu stripes, while decreasing its total width w_{Cu} . We can observe, by means of angle-resolved photoemission, a progressive transition from two-dimensional surface bands to one-dimensional quantum well states as w_{Cu} decreases. A direct comparison between surface states of infinite vicinals and nanostructures with the same d indicates a small upwards energy shift in the latter, which is well explained by assuming electron confinement in an infinite quantum well of size w_{Cu} . Nanostructure finite size effects are more straightforwardly observed in Fermi surfaces, which are asymmetrically broadened in the perpendicular direction. This effect is quantitatively analyzed and explained as due to the characteristic spectral broadening observed in photoemission from w_{Cu} -wide one-dimensional quantum wells.

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I. INTRODUCTION

Lateral nanostructures grown at surfaces, like quantum dots, stripes or atomic wires, are matters of intensive research due to their potential in different areas of nanotechnology. The basic electronic properties of these systems, like electronic states and wave functions, are still poorly known. This requires fundamental research using model systems and powerful analytical techniques, such as scanning tunneling microscopy and/or spectroscopy (STM/STS) and angle resolved photoemission (ARPES). Noble metal surfaces are excellent playgrounds to test the electronic interaction between the nanostructure array and the supporting substrate. The reason is the simplicity of its electronic structure, i.e., a well-defined two-dimensional (2D) free-electron-like surface state that scatters strongly at molecules, adatoms, point defects or step edges, thereby leading to one-dimensional (1D) or zero-dimensional (0D) confinement, electron interference phenomena, and 2D superlattice effects.¹⁻⁷

Vicinal (111) noble metal surfaces are particularly suitable to investigate surface electron scattering by ARPES.²⁻⁷ They usually display regular arrays of straight steps, such that the vicinal surface can be viewed as a 1D step superlattice, where the step-to-step distance d is the 1D lattice constant. Despite this simplicity, surface states in (111) surfaces vicinal to the (111) plane exhibit intriguing properties. Although they are the same Shockley-type states derived (or projected) from the L point of the bulk band structure, in vicinal surfaces they show d -dependent dimensionality and complex 3D-Fourier composition.²⁻⁴ Indeed, surface states are found to smoothly evolve from 1D quantum well levels confined within (111) terraces for large values of d , to 2D surface resonances modulated by the step array for small d , with a critical terrace size between the two regimes at around $d = 20$ Å.

Shockley-type surface states with changing dimensionality have also been observed in 1D stepped Cu stripes, i.e., step arrays with a finite number of steps.⁶ Such nanostructures

are self-assembled during Ag-induced periodic faceting of vicinal Cu(111) surfaces.^{8,9} A schematic side view description of this system is shown in Fig. 1(a). Submonolayer evaporation of Ag leads to a periodic hill-and-valley structure, made of close-packed, monolayer-thick Ag covering (112)-oriented facets and clean Cu stepped stripes, which are defined by their width w_{Cu} and their internal step spacing d . As a function of Ag coverage (Θ), Ag stripes become wider and Cu stripes narrower, i.e., the system smoothly evolves from very wide Cu stripes with a large number of steps and short step spacing d , to Cu stripes defined by a relatively wide ($d \sim 36$ Å), single (111) terrace.⁹ In such a two-phase system surface states split into distinct Ag-like states (above E_F), and Cu-like states (below E_F). As shown in Fig. 1(b), the Cu state exhibits a d -dependent 2D-1D transformation similar to that observed in vicinal crystals, i.e., a dispersing band for wide stripes with a small value of d (0.25 ML), and nondispersing quantum well (QW) peaks for the $d = 36$ Å wide, single Cu(111) terrace (0.8 ML).

In order to find the specific electronic features of periodic step arrays with finite dimensions, in this work we accurately analyze surface states of Cu nanostructures using ARPES. We observe differences with surface states from clean (or infinite) vicinal surfaces that can be entirely explained by the finite size w_{Cu} of the Cu nanostructure. On the one hand, there is a small energy shift for surface states in nanostructures with the same d , which amounts to the value expected for 1D QW confinement in w_{Cu} -wide nanostructures. Stripe size effects manifest very clearly in reciprocal space, where we observe, as a function of Ag coverage, an increasing broadening of the quasi-2D, ringlike Fermi surface in the direction perpendicular to the superlattice. The quantitative analysis indicates that this k -vector spreading is the one expected in photoemission from QW's of size w_{Cu} .¹⁰

II. EXPERIMENT

The photoemission experiments have been performed at the PGM beam line in the Synchrotron Radiation Center

(SRC) of the University of Wisconsin Madison, using a hemispherical Scienta 200 spectrometer. The photon energy is set to $h\nu=22$ eV, with p -like polarization of the light. Total energy and angular resolutions are 30 meV and 0.3° , respectively. Spectra are collected at 300 K in the whole 2D (k_x, k_y) space, with the scan angle of the Scienta parallel to the step array (k_y), while varying the emission angle in 0.3° steps in the direction perpendicular to the steps (k_x). The sample is vicinal to Cu(111) with a tilt angle of $\sim 13.6^\circ$ towards the $[\bar{1}\bar{1}2]$ direction, leading to an average step spacing $d_0=8.9$ Å that is close to the nominal value for Cu(335). The crystal is sputter-annealed in vacuum until sharp spot splitting is observed in the low energy electron diffraction (LEED) pattern. The periodic Ag/Cu hill-and-valley nanostructures of Fig. 1(a) are produced by deposition of Ag at 300 K, and post-annealed to 420 K. The STM analysis indicates a relatively well-defined step spacing d inside the Cu nanostripe.^{8,9} That is quantitatively determined by the standard deviation $\sigma = \langle \Delta d \rangle / d$, which is found to vary from 0.14 to 0.25 in the Ag coverage range shown in Fig. 1(a). Such values of σ are similar to those measured in infinite vicinal surfaces,³ proving that stepped nanostripes can be viewed as vicinal crystals with finite dimensions, in analogy to thin films versus bulk crystals. The presence of a periodic array of steps inside the nanostripe can also be inferred from the characteristic Umklapp bands observed in photoemission,⁶ or from the persistent splitting of the (0,0) spot in LEED.⁹

III. COVERAGE-DEPENDENT STEP SPACING AND STRIPE WIDTH

Ag-covered facets in Fig. 1(a) are oriented parallel to the (112) plane. Such particular orientation is explained by the good lattice matching between Ag close-packed rows and Cu(112) terraces.⁸ Since the step density in the (112) plane is

higher than in the (335) plane, (112)-oriented facets can only expand by adding steps from clean Cu nanostripes. This regime of (112)-facet growth, which is also called A-regime,⁹ saturates at a given coverage Θ_c . Beyond this coverage, further deposition of Ag leads, as sketched for 0.8 ML in Fig. 1(a), to a mixture of (112)–(335)-oriented facets in the so-called B-regime, which extends up to monolayer completion.⁹ From purely geometric arguments one can deduce the angle between the Cu nanostripes and the macroscopic (335) surface or the (111) plane, and from here, the Θ -dependent average step spacing d during the (112)-facet regime,

$$d(\Theta) = \frac{1 - \Theta}{1/d_{(335)} - \Theta/d_{(112)}}, \quad (1)$$

where $d_{(335)}=8.9$ Å and $d_{(112)}=6.25$ Å, respectively, stand for the lattice constants in Cu(335) and Cu(112).¹¹ Although Eq. (1) diverges at $\Theta=0.74$ ML, the saturation value Θ_c of the (112)-facet regime is reached before, due to the finite size of the Cu nanostripe. w_{Cu} is also coverage dependent, being determined from the elastic interaction between the system phases (Ag covered and clean Cu stripes), which in turn explains the periodic character of the faceted structure. As accurately studied by STM and spot-profile LEED (SPALEED) experiments,⁹ the long-range Θ -dependent periodicity of this Ag/Cu superstructure follows Marchenko's elastic theory,¹² where the Cu nanostripe width w_{Cu} is given by the following equation:

$$w_{Cu}(\Theta) = \kappa \times \frac{1 - \Theta}{\sin(\pi\Theta)}, \quad (2)$$

where κ is a constant related to a cutoff parameter and to a characteristic ratio of the elastic constants in the interacting phases. Both are generally unknown, but κ can still be determined empirically by fitting Eq. (2) to the STM or the

FIG. 1. (Color online)(a) Side view of the Ag/Cu periodically (period L_Θ) faceted nanostructure as a function of Ag coverage. Up to 0.6 ML, we distinguish an early regime with (112)-oriented facets, whereas a mixture of (335) and (112) facets appears near monolayer completion. In the (112)-facet regime, the density and size of these facets increases, thereby reducing the terrace size d in contiguous Cu nanostripes (width w_{Cu}). The latter display surface states with w_{Cu} -dependent dimensionality, evolving from quasi-two-dimensional bands in large Cu stripes with high density of steps (0.25 ML) to one-dimensional quantum wells in narrow Cu stripes (0.8 ML). This is proved by the dispersing behavior of their Cu surface state in the perpendicular direction of the step array shown in (b). The series of photoemission spectra have been taken with $h\nu=22$ eV and varying the emission angle in 0.5° steps. They clearly show a dispersing peak with 0.25 ML and a nondispersing QW feature with 0.8 ML.

FIG. 2. (Color online) Energy distribution curves for surface states in Cu nanostructures at increasing coverage. The spectra have been taken with $h\nu=22$ eV and correspond to band minima for dispersing peaks (clean, 0.25 ML and 0.45 ML) and intensity maxima for nondispersing, QW-like peaks (0.6 ML and 0.8 ML). The solid lines represent line fitting to the data. The peaks display a continuous downward shift towards the peak position of Cu(111) (dotted line), reflecting the size-dependent shift in terraces of increasing size, as previously observed in infinite vicinal surfaces (Refs. 4 and 14).

SPALEED data.⁹ In the (112)-facet regime such analysis has been accurately done for Ag-induced faceting of Cu(223) giving $\kappa=91$ Å,⁹ whereas for Cu(335) the available STM data indicate the same variation in $w_{\text{Cu}}(\Theta)$ during the (112)-facet regime.¹³ Thus, assuming $\kappa=91$ Å and making equal Eq. (1) and (2) we obtain the critical coverage at which the (112)-facet regime saturates during Ag-induced Cu(335) faceting, i.e., $\Theta_c=0.64$ ML and $w_{\text{Cu}}=d_c=36$ Å. Beyond this point, Eqs. (1) and (2) do not hold. Experimentally can be observed an abrupt transition to the mixed Ag-facet regime, where Ag-covered areas expand by coalescence of contiguous stripes. This leads to a smooth reduction in the length and the total number of Cu stripes, while keeping a constant width $d_c=36$ Å.^{9,13}

IV. SURFACE STATE CONFINEMENT WITHIN NANOSTRIPES

In Fig. 2 we show the photoemission energy distribution curve (EDC) spectra corresponding to the bottom of the surface band for increasing coverage. For 0.6 ML and 0.8 ML the surface state is not dispersing along k_x , as shown in Fig. 1(b), and hence their respective EDC in Fig. 2 corresponds to the QW spectrum with maximum intensity. d values are related to coverage via Eq. (1). The spectra have been fitted using a standard procedure, with a Gaussian line for the sur-

FIG. 3. (Color online) (a) Open circles, surface state peak shift in Cu nanostructures with respect to flat Cu(111) versus surface state peak shift in single crystal, infinite vicinals (filled dots and thin lines) with the same step spacing d . The upper scale indicates the absolute size of the nanostructure w_{Cu} at a given d . The dotted line represents the expected peak shift in an infinite one-dimensional quantum well of size w_{Cu} . The transition from surface state scattering at weak step barriers in wide stripes to full confinement within narrow Cu nanostructure boundaries is nicely observed. (b) Energy shift versus relative broadening with respect to flat Cu(111) for surface states in Cu nanostructures. Data points lie close to the universal behavior found for scattering in metallic steps [thick line (Ref. 7)], revealing the same nature of the scattering potential in all cases.

face state peak, a parabolic background, and a Fermi function. The result of the fit is shown as a solid line under every spectrum. We did not observe differences in the fit by using a Lorentzian and/or Gaussian convolution for the surface state peak, indicating a significant Gaussian broadening due to terrace width distribution effects. As a function of Θ (increasing d), the surface state shifts towards the peak position for Cu(111) at $E_0=E_F-0.391$ eV,^{4,14} and also becomes narrower. Only at 0.8 ML, i.e., beyond the transition coverage Θ_c to the mixed Ag-facet regime, the surface state shifts very slightly to higher energies. A decreasing, d -dependent energy shift and broadening in the surface state peak with respect to that of flat Cu(111) is the characteristic feature of infinite vicinal surfaces with terraces of increasing size.^{3-5,7,14} Thus, Fig. 2 qualitatively indicates that step edges are the dominant source of repulsive scattering for surface electrons inside nanostructures.

The surface electron scattering in Cu nanostructures and vicinal surfaces is quantitatively compared in Fig. 3(a), where we plot the d -dependent band shift ΔE , i.e., the shift of the peaks in Fig. 2 with respect to the Cu(111) surface state. Open circles and thick black lines correspond to Cu nanostructures, whereas small dots connected by a thin line are data points measured at 300 K in infinite vicinals and collected in Ref. 7. The top scale indicates the size of the Cu nanostructure w_{Cu} as determined from Eq. (2). Error bars refer to the left and the bottom scales, and are, respectively, determined from the fit to the data in Fig. 2 and following the criteria given in Ref. 11. ΔE for Cu nanostructures with relatively large width w_{Cu} match the corresponding values for infinite vicinal surfaces, whereas for small w_{Cu} , ΔE becomes slightly larger. This is simply explained by the increasing influence of the stripe boundaries and their much stronger scattering potential compared to monatomic steps. For large w_{Cu} values electron scattering is dominated by the significant number of mon-

atomic steps inside the nanostripe, which are known to behave as small (~ 1 eV Å) repulsive barriers for surface electrons.³ As w_{Cu} decreases, the stronger repulsive barrier at stripe boundaries contributes additionally to ΔE . The dotted line in Fig. 3(a) represents ΔE calculated for an infinite QW of size w_{Cu} , i.e., $\Delta E = (\hbar^2 \pi^2) / (2m^* w_{\text{Cu}})^2$ with $m^* = 0.41m_e$.³ It gives, within error bars, the energy shift for nanostripes at 0.6 ML ($w_{\text{Cu}} = 38.3$ Å) and 0.8 ML ($w_{\text{Cu}} = d_c = 36$ Å), i.e., stripes with only one or no step inside.

In order to qualitatively prove the nature of the electron barrier at the step, in Fig. 3(b) we plot the energy shift (ΔE) versus the change in surface state peak width with respect to flat Cu(111) (ΔW). The data again correspond to the peak analysis performed in Fig. 2, whereas the peak width in Cu(111) $W_0 = 50$ meV is taken from Ref. 7. The thick straight line corresponds to the universal, linear relationship empirically obtained from a number of systems, namely Cu(111) vicinals with different miscut as well as (111)-oriented, Ag/Cu striped structures.⁷ Such linear relationship between ΔE and ΔW was explained as due to the same dipolelike nature of the complex step barrier potential in all cases, despite that the barrier can have a different strength depending on the system. Although data appear more scattered in Fig. 3(b), we observe that the same linear trend holds in Cu nanostripes, in particular for narrow stripes that are defined by Ag-covered, (112)-oriented stripe boundaries. Thus, we conclude that the scattering potential is stronger in stripe boundaries with respect to monatomic steps, but its physical nature has not changed. Nonetheless, the strong scattering at nanostripe boundaries in the present case contrasts with the absence of dipole-barrier-related scattering in Cu nanostripes bordered by (111)-oriented Ag stripes.⁷ The difference should be thus explained by a distinct atomic structure of stripe boundaries, which in turn leads to a different smear-out charge or dipole moment. For (111)-oriented stripes the STM images reveal double step edges uphill and Ag decoration of monatomic Cu steps downhill. In the present case, the atomic arrangement at stripe boundaries is unknown.

V. SURFACE STATE BROADENING IN k -SPACE

Electron confinement in Cu nanostripes of reduced width leads to broadening of surface states in reciprocal space, as previously observed for surface electrons confined in Au(111) terraces.^{10,16} Such a size-dependent spectral broadening in Cu nanostripes is observed in constant energy surfaces, like the Fermi surfaces (FS) shown in Fig. 4. Here k_x and k_y , respectively, refer to the perpendicular and parallel directions relative to the average (335) surface plane. They have been determined from the electron kinetic energy E and the emission angle θ with respect to the average surface normal as $k_{x,y} = \sqrt{(2m/\hbar^2)E} \sin \theta$. Up to 0.6 ML, the dominant feature in Fig. 4 corresponds to a Cu-like quasi-2D FS ring centered at $k_y = 0$. As the coverage increases, the FS ring center shifts from $k_x = 0.36$ Å⁻¹ in the clean surface to $k_x = 0.46$ Å⁻¹ at $\Theta = 0.8$ ML. Both the shift and the ring position around $k_x \sim 0.4$ Å⁻¹ are purely artificial, since $\bar{\Gamma}$, i.e., the normal to the average plane of the stripe, rotates in real space

FIG. 4. (Color online) Fermi surface evolution for Ag/Cu faceted nanostructures as a function of coverage. The photoemission experiments were carried out with $h\nu = 22$ eV. The bright spot at $k_x \sim 0.33$ Å⁻¹ identifies the emission from Ag stripes, which is significant only beyond 0.6 ML. The interesting feature is the Cu-related Fermi surface ring. Its radius increases and it becomes broader along k_x , respectively, reflecting terrace size increase and stripe width decrease as a function of Θ (see Fig. 1). At 0.6 ML, the Cu ring collapses into a one-dimensional QW-related vertical streak at $k_y \sim 0.16$ Å⁻¹. The dotted lines indicate the position of the intensity profiles shown in Fig. 5.

towards the [111] direction as Θ increases. Although the FS ring in nanostripes, as in infinite vicinals, should be found at a shifting zone boundary edge π/d (downwards in Fig. 4), such a shift is overcompensated by the physical rotation of $\bar{\Gamma}$ towards the (111) direction (upwards shift in Fig. 4). On the other hand, the surface state emission from Ag-covered facets is the bright spot that abruptly sets in for 0.8 ML at $k_x = 0.33$ Å⁻¹, remaining as the unique feature in the fully covered surface. The shift in the FS ring center from the clean ($k_x = 0.36$ Å⁻¹) to the Ag-covered ($k_x = 0.33$ Å⁻¹) surface could reflect a small tilt (0.8°) of the (111) plane in the Ag film with respect to the (111) plane in the Cu substrate, as found in Ag/Cu(211).¹⁷ The sudden enhancement of the Ag-related intensity at 0.8 ML is naturally explained if surface states in Ag-covered (112) facets lie beyond the Fermi level, but shift closer to E_F in (335)-oriented facets in the mixed Ag-facet regime.

Figure 4 reflects the 2D-1D transition of the Cu nanostripe surface state through the smooth transformation of its Fermi surface. As a function of coverage, the Cu FS ring keeps its circular shape up to 0.6 ML,¹⁵ although it becomes larger in size and sharper along k_y . Both effects, respectively, reflect the downwards shift and the decreasing width of the surface state peak shown in Figs. 2 and 3, which in turn are connected to the increasing step spacing d within the Cu nanostripe. By contrast to k_y , the FS ring gets broader along

FIG. 5. (Color online) Momentum distribution curves across the Fermi surfaces perpendicular (left) and parallel (right) to the nanostripes, as indicated with dotted lines in Fig. 4. The k_x scale is referred to the ring center in Fig. 4, nominally found at the zone boundary of the nanostripe step array π/d . Solid lines are fits to the data using Gaussian functions. The increasing asymmetry in peak width for parallel and perpendicular directions is explained as due to stripe size effects.

k_x and converts into a single streak for QW states at 0.8 ML coverage (in this case, the bright spot due to the Ag surface state emission must be disregarded). The Θ -dependent, asymmetric broadening of FS rings is the most straightforward signature of the finite size of the Cu nanostripe, as discussed below. This effect is more quantitatively studied in the momentum distribution curves (MDC) shown in Fig. 5. Here we represent the Fermi level intensity profiles in the direction perpendicular and parallel to the steps crossing the FS center, as indicated by the yellow lines in Fig. 4. The two Fermi crossings along k_x are rather symmetric at low Θ , but the right-hand side peak becomes relatively wider and more intense as the coverage increases, due to overlap with Ag surface states above E_F . Thus, for a numerical analysis we focus on the left-hand side peak. In order to extract the peak width along k_x (Δk_x) and k_y (Δk_y) we fit the data with Gaussian lines in both directions. In the clean surface the fit is forced in the outer part of the peak, away from the ring center at $k_x = k_y = 0$. There, the Fermi edge crossing is poorly defined due to the proximity and the significant broadening of the surface state at the band bottom (see Fig. 2). Defining the peak width asymmetry as $\Delta k_{xy} = \Delta k_x - \Delta k_y$, this varies from $\Delta k_{xy} = 8 \pm 6 \text{ mÅ}^{-1}$ (HWHM) for the 2D step array on the clean Cu(335) surface, to $\Delta k_{xy} = 78 \pm 6 \text{ mÅ}^{-1}$ in the 36 Å wide stripe for 0.8 ML.

In regular photoemission spectra like those of Figs. 1(b) and 2, surface peak features are broadened by both photohole lifetime and terrace width distribution effects. Assuming isotropic effective masses and lifetime variations, such broadening is equally transferred to energy contours and MDC spectra along both k_x and k_y directions, leading to a symmetrically broadened, circular FS. Nonetheless, the terrace width distribution is expected to cause a residual Δk_{xy} asymmetry by spreading the zone boundary π/d along k_x .⁵ However, as discussed before, the average surface plane in the

FIG. 6. (Color online) Asymmetric broadening ($\Delta k_{xy} = \Delta k_x - \Delta k_y$) in momentum distribution curves at the Fermi energy, as determined from the line fitting in Fig. 5. The red dots and the straight lines represent the spectral broadening width in photoemission from infinite quantum wells of size w_{Cu} , as calculated from Eq. (3) and $N > 1$. The close relationship between both applies in the whole coverage regime, thereby defining Δk_{xy} as the straightforward feature that characterizes finite size effects in nanostripes. The inset shows a schematic description of the electron potential and wave function within the stepped Cu nanostripe. The infinite potential at stripe boundaries leads to the quantum well modulation ($N = 2$ in the inset) of the step superlattice electron wave function inside the nanostripe.

nanostripe (or $\bar{\Gamma}$) is also d -dependent, such that any spread (shift) in π/d is largely compensated at 22 eV photon energy, by a corresponding spread (shift) in $\bar{\Gamma}$. This compensating effect also explains the reduced asymmetry Δk_{xy} found in the MDC cuts of Fig. 5 for the clean Cu(335) surface, as well as in MDC cuts in Cu(221).⁵ Therefore, since the terrace width distribution broadening is similar in clean Cu(335) surface and in Cu nanostripes, we do not expect a significant terrace width distribution contribution to Δk_{xy} in Fig. 5, and hence the thickness-dependent Δk_{xy} asymmetry can be mostly explained by finite size effects in nanostripes. Furthermore, assuming that all lifetime, terrace width distribution and stripe size broadening contributions add up in MDC peaks, Δk_{xy} is also a good quantitative estimation of such size effects.

Photoemission from lateral QWs on a surface leads to nondispersing energy levels with characteristic wave vector broadening.¹⁰ In a first approach, the wave-vector dependent photoemission intensity is proportional to the probability density inside the QW, and this allows one to probe, and even retrieve,¹⁶ electron wave functions in real space. For the stepped Cu nanostripe with strongly repulsive stripe boundaries and relatively weak step barriers, we expect step superlattice states modulated by nanostripe QW wave functions, as schematically shown in the inset of Fig. 6. Thus, the probability density probed in photoemission can be reasonably approached by that of infinite QWs of size w_{Cu} ,¹⁰

$$I(k_x) \propto \frac{1 - (-1)^N \cos(k_x w_{\text{Cu}})}{\left[k_x^2 - \left(\frac{\pi N}{w_{\text{Cu}}} \right)^2 \right]^2} \times N^2, \quad (3)$$

where N refers to the quantum number of the 1D infinite QW. Interestingly, Eq. (3) leads to peaklike features whose width depend on w_{Cu} and not on N , except for the bottom level $N=1$. As deduced from the spectra in Fig. 1(b), in the whole Θ range the Fermi energy lies far above the $N=1$ level (band bottom), and hence the size-related asymmetry Δk_{xy} at E_F can be compared, into a first approach, with the width of the spectral intensity given by Eq. (3) for $N > 1$. This is done in Fig. 6, where we plot the asymmetry Δk_{xy} of the FS rings of Fig. 5 (white data points) together with the spectral intensity broadening (HWHM) for QW's of the corresponding size w_{Cu} (filled dots and straight lines), calculated with Eq. (3) for $N > 1$. Data points lie very close to the calculated values, even for the widest stripes at 0.25 ML, thereby proving that the asymmetric broadening in Fermi surfaces is clearly a consequence of the finite size of Cu nanostripes and the strong electron confinement inside.

VI. SUMMARY

In summary, finite size effects in stepped Cu nanostripes manifest clearly in their Fermi surface, which evolves from a two-dimensional ringlike feature in very wide stripes to an asymmetrically broadened ring for narrow stripes. Stripe boundaries, which are defined by (112)-oriented Ag-covered facets behave as totally reflecting barriers that confine surface state electrons. This can be deduced from the slight surface state energy shift with respect to infinite vicinal surfaces with the same terrace width, as well as from the quantitative analysis of the asymmetric broadening observed in Fermi surfaces.

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- ¹¹The direct connection between d and Θ in Eq. (1) allows a simple control of Ag coverage either from the (0,0) spot splitting in the LEED pattern or the Umklapp bands in photoemission. Assuming Eq. (1), the uncertainty in LEED splitting ($\Delta d \sim \sigma \times d$) determines the uncertainty in coverage, which we find to vary slightly around 0.05 ML.
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