Thermal Damping of Surface-State Electrons at a Step

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The temperature dependent damping of quantum mechanical interference patterns from surface-state electrons scattering off steps on Ag(111) and Cu(111) has been studied using scanning tunneling microscopy and spectroscopy in the temperature range 3.5 K-178 K. The thermal damping of the electron standing waves is described quantitatively within a simple plane wave model accounting for thermal broadening due to the broadening of the Fermi-Dirac distributions of sample and tip, for beating effects between electrons with different $\mathbf{k}_{//}$ -vectors, and for inelastic collisions of the electrons, e.g. with phonons. Our measurements reveal that Fermi-Dirac broadening fully explains the observed damping for Ag and Cu. From the analysis of our data lower limits of the phase-relaxation lengths at the Fermi energy of the 2D electron gas of $L_\Phi(E_F) \geq 600$ Å at 3.5 K and ≥ 250 Å at 77 K for Ag(111), and of $L_\Phi(E_F) \geq 660$ Å at 77 K and ≥ 160 Å at 178 K for Cu(111) are deduced.

I. Introduction

Shockley type surface states exist in the Γ-L projected bulk band gap of the (111) surfaces of noble metals. They form a two-dimensional (2D) nearly free electron gas which is subjected to scattering at surface imperfections such as steps and point defects leading to periodic spatial oscillations of the electronic local density of states (LDOS). The LDOS-oscillations at surfaces can be understood as interference of the electron wave traveling towards the scattering defect with the back-scattered one. The resulting quantum mechanical interference patterns can be spatially resolved in scanning tunneling microscopy/spectroscopy (STM/STS) [1,2]. The STM acquires a quantity roughly proportional to the surface LDOS in spectroscopic $dI/dV(E,x,y)|_z$ maps, whereas it displays the integral of the LDOS from (E_F to E_F + eV) in conventional $z(x, y)|_{I,V}$ topographs. A prerequisite for the standing waves to appear is a sufficiently long phase coherence length L_Φ, the mean length an electron travels without loosing its phase memory. Several of the former STM studies of standing waves point out the lack of knowledge on the phase coherence length of the 2D electrons. Also the mechanisms underlying the decay of interference patterns observed at elevated temperatures are not clarified yet. The former absence of measurements reporting standing waves on Cu(111) at 300 K was speculatively attributed to inelastic scattering, whereas thermal broadening of the Fermi-Dirac distributions was invoked for room temperature measurements on Au(111). The question arises whether STM can furnish quantitative information on inelastic scattering of 2D electrons. Collisions of an electron with static scatterers like steps or adsorbates do not influence the phase-coherence. In conducting systems, L_Φ is reduced by inelastic scattering processes like electron-electron interaction at appreciable electron energy, or by electron-phonon interaction at higher temperatures [3. In contrast to ARPES, STM offers the possibility to determine *locally* the phase-relaxation length L_Φ of surface state electrons by analyzing the damping of the LDOS-oscillations. In this paper we derive first absolute estimates of $L_\Phi(E_F, T)$ for the Shockley type surface states of Ag(111) and Cu(111).

II. Experiment

The measurements were acquired with a custom-built 4K-5T STM operating in UHV [4]. The Ag(111) and Cu(111) surfaces have been cleaned by sequential cycles of Ar^+ sputtering at 300 K and subsequent annealing to T = 870 K and T = 820 K, respectively. After this procedure, the surfaces had terraces of more than 2000 Å width with a surface coverage of ≈ 0.02% of a mono-layer (ML) impurities of unknown chemical identity. In our STM measurements the bias voltage V is applied to the sample. The electrochemically etched W tip has been prepared by field emission and by controlled indentations into the surface.

III. Results and Discussion

Our investigation of the spatial damping of standing waves is mostly based on constant-current line-scans taken perpendicularly to steps at various sample temperatures. The damping of quantum interference patterns as measured with STM is caused by a combination of inelastic scattering processes, Fermi-Dirac broadening and beating between electrons with different k-vectors. To compare the damping strength of these different contributions we define, in addition to L_Φ for inelastic processes, the following apparent coherence lengths. The expression of Fermi-Dirac broadening defines $L_{FD} \approx 0.011\ \hbar^2 k / (m\ k_B\ T)$, where $\hbar$ is the Planck constant and m the effective mass of the surface state electrons [4]. At small bias voltage V, the beating of the electrons with different k-vectors defines the length $L_{\Delta V} \approx 0.025\ \hbar^2\ k_F / (m\ eV)$. Depending on the chosen conditions (V,T) one of these three damping lengths is shortest and dominates the decay.

We present in figure 1(a) line scans taken at V = 10 mV from 3.5 K to 77.3 K on a Ag(111) terrace adjacent to a descending step. The damping of the standing waves with increasing T is clearly visible. The solid lines are fits using a simple plane wave model by putting $L_\Phi = \infty$ [4]. The data and the fitted function coincide almost perfectly, except in the immediate vicinity of the step edge where the model is not valid. The spatial damping is dominated by L_{FD} at high T, and by $L_{\Delta V}$ at low temperatures. It is clear from the fits that $L_\Phi > L_{FD}, L_{\Delta V}$ in the experiment. Within our model the temperature dependent damping of the standing waves is very well described by the Fermi--Dirac broadening alone. Therefore we can only give lower limits for the phase-relaxation length. For Ag(111) surface-state electrons L_Φ is estimated to be $L_\Phi(E_F) \geq 600$ Å at 3.5 K and ≥ 250 Å at 77 K.

For Cu(111), k_F is larger than for Ag(111) and with it also $L_{FD}(E_F)$ for a given temperature. At the Fermi energy Fermi-Dirac broadening is hence expected to play a smaller role for Cu(111) than for Ag(111). This explains why standing waves can be observed in constant current images on Cu(111) up to room temperature [5]. Beating effects should also be smaller for Cu(111) due to its steeper dispersion in the vicinity of E_F. Despite the smaller STM intrinsic damping, inelastic scattering effects still remain small. Our results of the temperature induced spatial damping on the Cu(111) surface represented in Figure 1b are as for Ag(111) fully reproduced by our model assuming $L_\Phi = \infty$. Again, there is perfect agreement between model and experiment

and the observed apparent coherence loss can entirely be explained in the framework of Fermi-Dirac broadening and small beating effects. We thus estimate $L_\phi(E_F) \geq 660$ Å at 77 K and ≥ 160 Å at 178 K.

IV. Conclusion

In conclusion, the quantum interference of surface state electrons near mono-atomic steps on Ag(111) and Cu(111) has been studied in the temperature range of 3.5-178 K. The temperature dependent spatial damping of constant-current line-scans at steps are perfectly explained by elastic tunneling theory. Thus, the phase-relaxation length L_ϕ of 2D-electrons is larger than the damping length L_{FD} due to the Fermi broadening of the STM beam. Nevertheless, we were able to derive lower bounds for $L_\phi(E_F, T)$ pointing to significantly longer lifetimes than all data currently available for surface states

References

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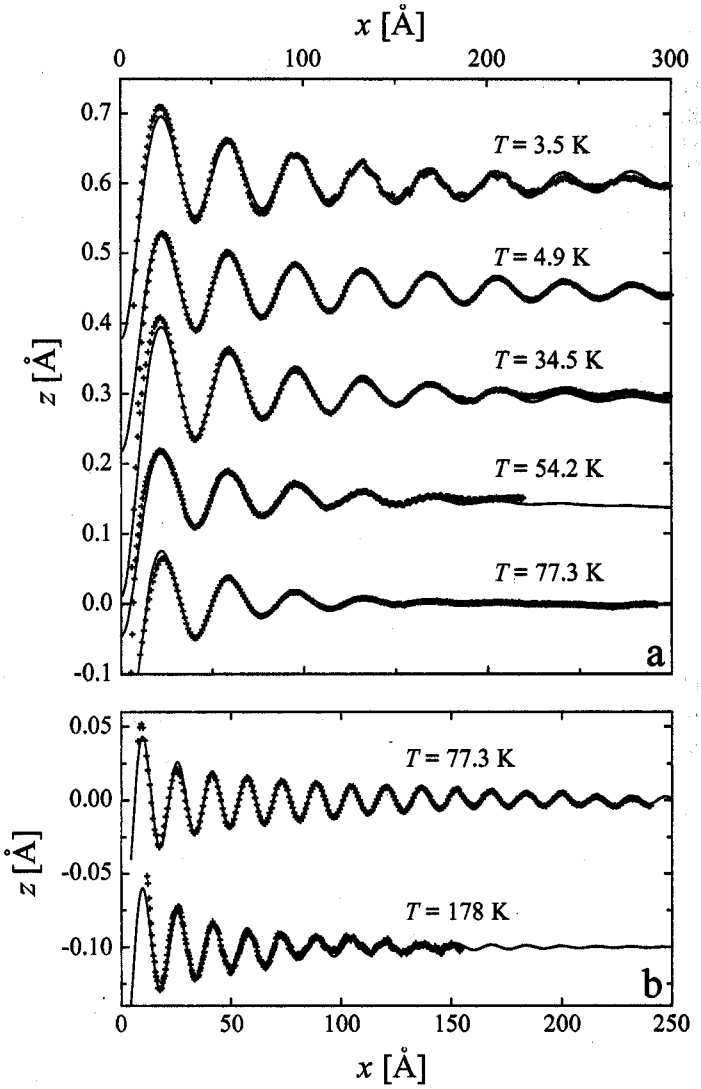

Fig. 1. (a) Ag(111) and **(b)** Cu(111) constant-current linescans taken at V = 10 mV on a terrace adjacent to a descending step (for Ag(111) I = 1.0 nA and for Cu(111) I = 0.4 nA, 0.1 nA at 77.3 K, 178 K, respectively). The data have been displaced vertically for clarity. The solid lines are fits using a model based on the elastic tunneling theory [4].