Electronic Transport in Ultrathin Gold Films on Si(111)

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The morphology and electronic transport of ultrathin Au films with thicknesses d = 1 - 5 monolayers (ML) deposited on Si(111)7 × 7 surfaces is investigated by in situ scanning tunneling microscopy and electrical resistance measurements for temperatures T = 2 - 300 K. With decreasing film thickness, i.e. decreasing sheet conductance G_s, a transition from a weakly conducting regime described by a logarithmic temperature dependence to an insulating regime occurs. In the insulating regime, the temperature dependence is described by G_s ∝ exp[-(T_0/T)^α] with an exponent α which gradually changes from 0.69 to 1 with decreasing film thickness. In contrast, for the Si(111)6 × 6-Au reconstruction obtained after annealing, an exponent α = 1/2 is found suggesting the formation of a soft Coulomb gap due to electron-electron interaction.

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1. INTRODUCTION

The growth, morphology, and electrical resistance of metallic films has been studied in great detail for several decades to investigate the influence of the film structure on the electronic properties. However, the electronic transport of very thin metallic films epitaxially grown on silicon substrates with thicknesses d in the monolayer (ML) and sub-ML range has attracted interest only recently. For instance, the magnetoresistance of Ag films on Si(111)7 × 7 can be explained by weak antilocalization effects for d > 3 ML whereas thinner films show properties which cannot be described quantitatively by any theory 1. By further decreasing the metal coverage on
Si(111)7×7 to below 1 ML, the surface reconstructs to the Si(111)$\sqrt{3} \times \sqrt{3}$ superstructure which seems to have a higher surface conductivity than the clean Si(111)7×7 surface. More interestingly, deposition of 0.2 ML Au on a vicinal Si(111) substrate gives rise to the formation of Si(557)-Au facets which exhibit unusual electronic properties as observed in photoemission experiments. On Si(111)4×1-In, micro-four-point probe measurements indicate a strong anisotropy of the surface conductance at room temperature. On Si(557)-Au a detailed analysis of the temperature-dependent resistance was hampered by the contribution from the bulk Si substrate. The data suggest that the electrical conductance of Si(557):Au is low. Here we have characterized 1-5 ML-thin Au films on Si(111) and measured their electrical resistance with decreasing thickness in order to reach the ML regime from the metallic side.

2. EXPERIMENTAL

Si(111) substrates (p-type, resistivity $\rho = 1.5 \ \Omega \cdot \text{cm}$) were cleaned in an ultra-high vacuum (UHV) system (base pressure $1 \times 10^{-10}$ mbar) by several cycles of electron-beam heating from the back to a substrate temperature $T_S = 750 - 850^\circ$C measured by an optical pyrometer. Finally, the substrate was flash annealed to $T_S = 1000^\circ$C to yield the Si(111)7×7 reconstructed surface. After cooling down to room temperature, 1-5 ML Au were deposited with a rate of $\approx 1$ ML/min from a tungsten crucible heated by an electron beam. The evaporation rate was controlled with a quartz crystal monitor. Here, 1 ML Au corresponds to a film thickness of 0.236 nm assuming a preferred growth of Au (111) with a surface atom density of $1.4 \times 10^{15}$ cm$^{-2}$. Hence, all Si sites of the initial Si(111) surface ($7.8 \times 10^{14}$ cm$^{-2}$) are covered by Au atoms for a thickness of 0.6 ML Au.

Structural characterization was done in situ by scanning tunneling microscopy (STM) at room temperature using chemically etched W tips which were further cleaned in situ by several cycles of Ar$^+$ sputtering and annealing.

Subsequently, 10-nm thick Au contacts were evaporated through a micromachined mask moved in front of the substrate without breaking the UHV. The mask defines a shadowed area of width $w = 0.31$ mm and length $L = 0.13$ mm whose resistance is measured in the temperature range $T = 2 - 300$ K by an ac-resistance bridge. Four spring-loaded needles are pressed onto the Au pads for electrical contact.