論文内容の要旨

論文題目

Study of Transport Properties of Low-Dimensional Metallic Systems on Si Surfaces

(シリコン結晶表面上に形成される低次元金属系の電子輸送特性の解明)

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Reduction of metal film thickness down to the electron wavelength induces energy quantization by the quantum size effect, resulting in the formation of quantum well states. Recently, there has been growing interest in such quantum films on solid surfaces. In contrast to a freestanding metal film, these quantum well states (resonances) have been reported to show additionally intriguing physical properties such as spin polarization, anomalous in-plane dispersion, and oscillation of the superconducting transition temperature with thickness.

In the present work, transport properties of quantum well states confined in Ag films prepared on the Si(111)4×1-In are investigated by a newly developed system for conductivity measurements, comparing with the results of Angle resolved photoemission spectroscopy (ARPES) measurements and the tight-binding calculations. This thesis mainly consists of two parts.

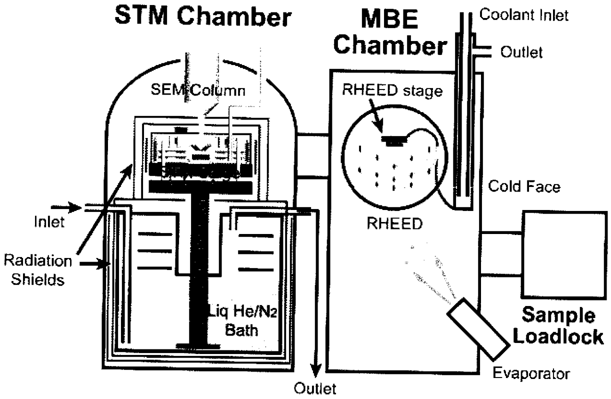

Figure1　Schematic drawing of the VT4tipSTM whole system.

In the first part, we have developed the variable-temperature independently-driven four-tip scanning tunneling microscopy (VT4tipSTM) [Fig.1], and I improved to perform stable measurements of my target system, Ag/Si(111)4×1-In, and other various kinds of nanodevices.

At first, the efficient cooling system and the units for vibration isolation are introduced to the main chamber. Secondly, an micro channel plate (MCP) for scanning electron microscopy (SEM) detector, new cables, and a test kit are installed for the stable measurements. Thirdly, the flow type cooling system and Reflection high energy electron diffraction (RHEED) spot intensity monitoring system are added to the preparation chamber. Finally, the voltage differential amplifier is designed and installed in the preamplifier for the measurements of a low-resistance sample.

The STM tips have great advantages as electronic probes because they allow arbitrary configurations and have high spatial resolution. Moreover, as the four tips are positioned in arbitrary arrangements at aimed areas on the sample surface, the 4-tip STM can measure anisotropic conductivity by a square arrangement without the effect of contact resistance. We can obtain transport properties of low dimensional systems (ultra-thin films, nanowires, quatum dots, etc.) and several nanoscale devices by *in-situ* measurements without any processes to make electrodes on the sample. Besides, the cooling capability allows us not only to suppress thermal perturbation but also to perform more advanced study of physical phenomena, such as superconductivity, localization, and various kinds of phase transitions.

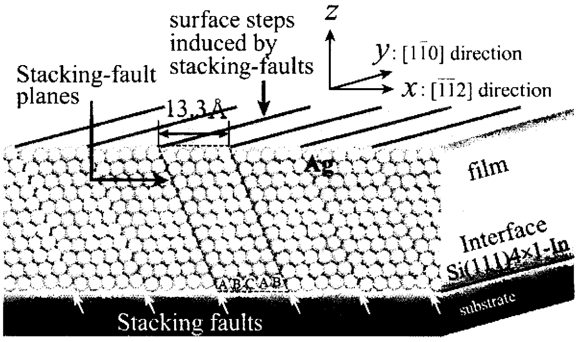

Figure2 Schematic image of Ag(111) ultra-thin film prepared on Si(111)4×1-In based on the stacking-fault model.

The second part of this thesis deals with the transport properties of the Ag films on the Si(111)4×1-In surface.

Recently, it has been reported that uniform Ag(111) thin films which have stacking-fault planes with ×4 period (~13.3Å) [Fig.2] can be grown epitaxially on atomic-chain like surface superstructure, Si(111)4×1-In surface, by the two step growth method. In advance, I have reported that the quantum well states (QWSs) in the Ag/Si(111)4×1-In have highly anisotropic electronic states revealed by ARPES measurements. They show a free-electron like parabolic dispersion along the In-chain direction but almost a flat one in the perpendicular to In-chain direction.

But in general, stacking faults are expected to give only small perturbation to the electronic states in fcc noble metals, so this change of the QWS from isotropic Ag film are considered to be curious results

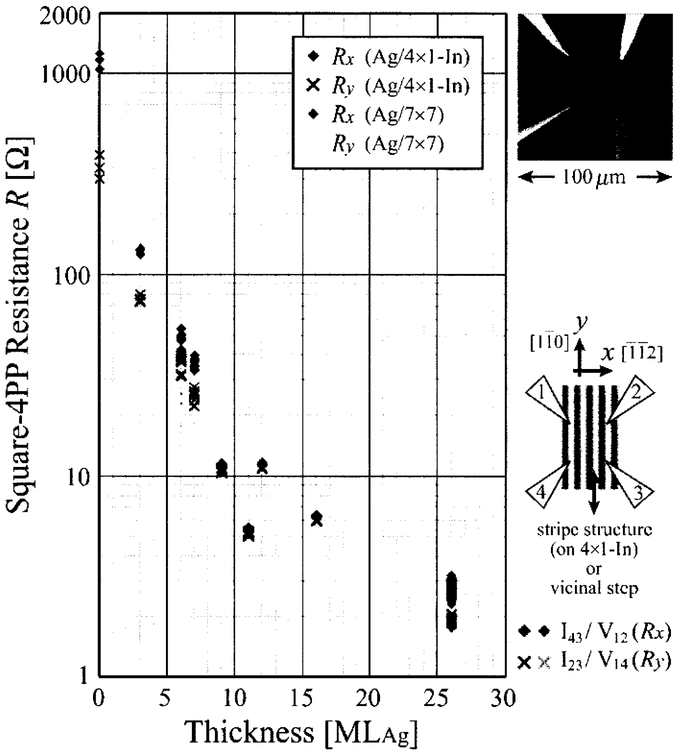

Figure3 The relation between the film thickness and the square-4PP resistance. An SEM image during measurements and the measurement schematics are indicated.

and the conductivity behavior of QWSs in the Ag/Si(111)4×1-In is very interesting to measure.

Therefore I have measured transport properties of this quasi-1D quantized states using the VT4tipSTM mentioned above by the square micro 4-point probe (4PP) method.

As a result, anisotropic conductivity was clearly detected at 3-16 MLAg, although the measured conductivity was isotropic at 26MLAg on Si(111)4×1-In [Fig.3]. Here 1MLAg means 1 atomic layer of Ag(111) and 1.4×10^{15} [atoms/cm^2], which is the surface atomic density of Ag(111)1×1. 1MLAg thickness corresponds to 2.36Å.

The origin of the anisotropic conductivity is discussed in the view points of (i) anisotropic electronic states and (ii) anisotropic interface scatterings. I estimated the contributions of the electronic states and the interface scatterings to the measured anisotropic conductivity by solving the Boltzmann transport equation in the diffusive transport region.

The contribution of each mechanism to the anisotropic conductivity is revealed to be classified on thickness.

The anisotropic conductivity is mainly due to the anisotropic surface scatterings at 3-5MLAg. At 6-7MLAg, both anisotropic electronic states and anisotropic surface scatterings are equally contribute to the measured anisotropic conductivity in square-4PP measurements. According to the STM observations by Uchihashi, the clitical thickness of the peculiar stripe structures with periodic stacking-fault planes is 6MLAg and this stripe structures are grown uniformly in large areas. At 11-16MLAg, effects of anisotropic surface scatterings are reduced by appearance of the flat regions at the film surface. These flat regions are caused by structural relaxation. The stacking-fault planes are considered to remain under the flat surface regions in the film at only near the film/4×1-In interface. The contribution of the anisotropic electronic states to 4PP-measured anisotropic conductivity is so small compared with that of the anisotropic surface scatterings, that the total anisotropic ratio A ($A \times 100$ [%]) decrease as films become thicker. As the thickness get larger to 26MLAg, the conductivity turns into isotropic because of the growth of flat regions without stacking-fault stripes and the reduction of the contribution from the surface scatterings compared to the bulk region.

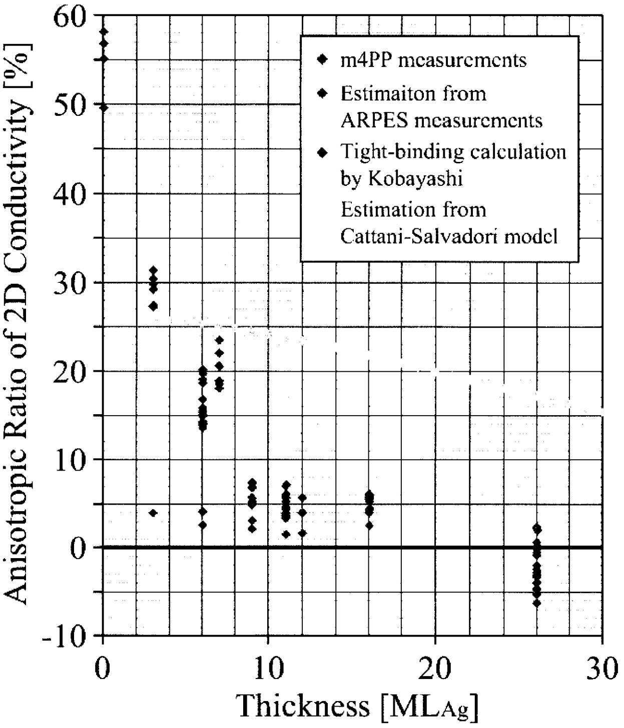

Figure4 Anisotropic ratio of 2D conductivity in Ag/Si(111)4×1-In with changing the film thickness.

Here we define x-direction as $[1\bar{1}0]$ perpendicular to the stacking-fault planes in the Ag films and In-chains at the interface, and y-direction as $[\bar{1}\bar{1}2]$ parallel to the stacking-fault planes in the Ag films and In-chains at the interface.

In the discussion above, the electron scatterings due to stacking-fault planes are taken into account by the deformation of the quantized Fermi surfaces and quantized band structures. When the probe spacing is reduced down to tens of nm by using carbon nanotube tips, Ag films on Si substrates are no longer the ideal 2D systems. Then I have estimated the resistance due to stacking-fault planes in the film by treating stacking-fault planes as tunnel barriers in ballistic region for more minitualized measurements in the near future. The square-4PP resistance is considered to be larger than the present results. When this tunnel resistance is dominant compared to the diffusive transport which I have adopted in case of μm-scale probe spacing, the difference of film resistivity between thickness, $\rho_y - \rho_x$, may depend on probe spacing.

The square micro-4PP temperature-dependent conductivity measurements showed the almost constant value at 6ML$_{\mathrm{Ag}}$ thickness irrespective of temperature, while the semiconducting behavior at 3ML$_{\mathrm{Ag}}$ were observed in which the conductivity decreased with decreasing temperature [Fig.5].

The constant conductivity which does not depend on temperature at 6ML$_{\mathrm{Ag}}$ can be explained by the dominant mechanism of the carrier flow in the film, the interface scatterings which are independent of temperature.

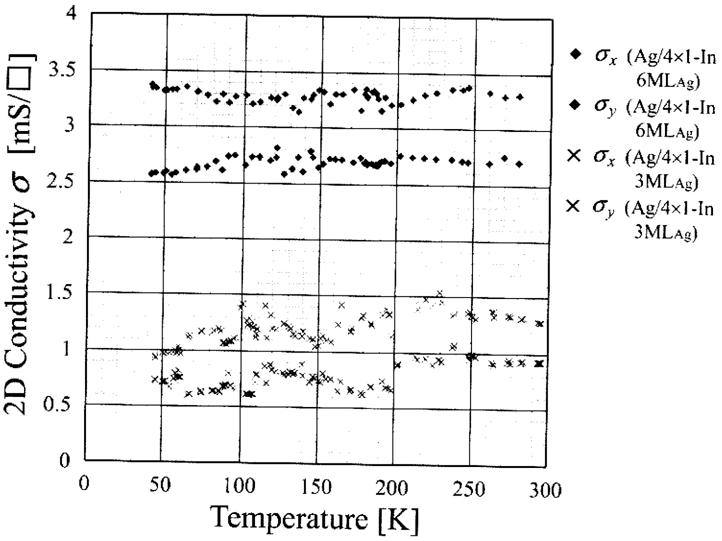

Figure5 Temperature dependence of 2D conductivity of 3ML$_{\mathrm{Ag}}$ and 6ML$_{\mathrm{Ag}}$ Ag films on Si(111)4×1-In.

The semiconducting behavior of the temperature dependence at 3ML$_{\mathrm{Ag}}$ cannot be explained by the activation tunneling current which is the popular effect for discontinuous films, because the continuous film has been already completed at 3ML$_{\mathrm{Ag}}$ in the case of the Si(111)4×1-In substrate. The effect of the weak localization is conceivable, but it has to be examined by magnetoresistance measurements in the further study.

The QWS confined in the Ag ultra-thin film on the Si(111)4×1-In has anisotropic electronic properties due to the modulation induced by one-dimensional surface superstructure 4×1-In, at the film/substrate interface. This indicates that the electronic/transport properties of QWSs can be controlled by interface atomic layer.

By synthesizing the results from different viewpoints such as the square-4PP conductivity measurements, ARPES measurements, and theoretical calculations, I have clarified the important factor in electronic states and atomic structures to determine the behavior of electronic conductivity.

My studies show an example to understand the transport properties of atomically controlled epitaxial quantum metal films beyond the existent mesoscopic systems realized by lithography techniques.