Molecular Physics Reports **40** (2004) 62-66

QUANTUM SIZE EFFECT IN Ag ISLANDS FORMED ON Si(111)-(7 × 7)

J. Gutek[1], R. Czajka[1], S. Suto[2], A. Wawro[3], and A. Kasuya[4]

[1]*Institute of Physics, Faculty of Technical Physics, Poznań University of Technology Nieszawska 13 A, 60-965 Poznań, Poland*

[2]*Dept. of Physics, Graduate School of Science, Tohoku University 980-8578 Sendai, Japan*

[3]*Institute of Physics, Polish Academy of Sciences Al. Lotników 32/46, 02-668 Warsaw, Poland*

[4]*Center for Interdisciplinary Research, Tohoku University Aoba-ku, 980-8578 Sendai, Japan*

Abstract: Nanometer scale metallic structures on Si(111)-(7×7) substrate have been created by Molecular Beam Epitaxy (MBE) technique and investigated by means of Scanning Tunneling Microscopy and Spectroscopy (STM/STS). Due to limited thickness of metallic islands (few to several mono-atomic layers) Quantum Size Effects (QSE) were observed. In our experiments small Ag islands of varying heights have been grown on Si(111)-(7 × 7) surface. Scanning Tunneling Microscopy revealed the presence of atomically flat islands with heights up to a few nanometers. Scanning Tunneling Spectroscopy (STS) measurements enabled us to measure the *I-V* curves at every point of the recorded topography image. The calculated d(ln*I*)/d(ln*V*) *vs.* *V* (bias polarization) curves showed peaks around the Fermi level, which may be assigned to the QSE on these islands. A simple model [1] was used to estimate the total width of the quantum well which includes the width of Ag wetting layer and the length of the electron wave decay on both sides of the quantum well.

1. INTRODUCTION

Recently designed ultra-small electron devices based on Coulomb Blockade and Quantum Effects [2] are used in construction of digital circuits with typical scale of few nanometers or less. The basic physics of such devices as Single-Electron Transistors (SET's) and nanoscale Field Effect Transistors (FET's) are well known. Seeking proper materials and creation of useful devices becomes an important issue. The Quantum Size Effect [3-5] appears in low-dimensional systems with thicknesses of the order of de Broglie wavelength of electrons confined in it. These effects, originating from the electron confinement, are revealed as a change of electronic properties (*e.g.* local density of states (LDOS), electronic conductivity, *etc.*) when at least one of the structure dimensions is intensely reduced. Thin films or thin metallic islands on semiconductor substrate exemplify nanostructures where electrons are confined from one or all directions respectively by vacuum and by the metal-semiconductor interface. Thus flattop islands are perfectly suitable for Quantum Size Effect investigations. The only drawback is the fact that most experimental techniques as inelastic electron tunneling spectroscopy (IETS) [6] or angle-resolved photoemission spectroscopy (ARP) [7] provide results which are the averages over a large number of islands with different heights. STM/STS technique enables investigations of these systems with a high spatial resolution including determination of the LDOS and their changes associated with Quantum Size Effects.

Our work was devoted to creation of nanometer scale metallic structures on Si(111)-(7 × 7) substrate and Quantum Size Effects investigation in such systems caused by the limited thickness (few to several mono-atomic layers) of metallic islands. STM/STS measurements provide a clear picture of size quantization as well as correlation between the electronic properties and thickness of an individual island.

2. EXPERIMENTS DETAILS

The substrate used in our experiment was cut from Si(111) wafer. The sample was *n*-type silicon with resistivity between 0.015-0.020 Ωcm. Silver was deposited at room temperature by means of MBE using OMICRON EFM3 source. The coverage of Ag (10 ML) resulted in the formation of islands of few to several monolayers in height. AFM (Atomic Force Microscopy) technique was used to determine the surface coverage of Ag. The coverage was defined by evaluating the volume of deposited material visible on the Si(111)-(7 × 7) substrate (1.5 ML of Ag). All STM measurements were performed at room temperatures in an UHV system with the base pressure of about 6.0×10^{10} Torr using OMICRON STM/AFM system. We used electrochemically etched tungsten tips.

3. RESULTS AND DISCUSSION

Deposition of about 10 ML of Ag resulted in the formation of atomically flat islands of different heights. The whole silicon surface was coated with thin Ag islands, and therefore there were not visible spots with the Si(111)-(7×7) reconstruction (Fig. 1). Topography measurement revealed the presence of flattop islands with heights up to a few nanometers, where the quantum size effects were expected.

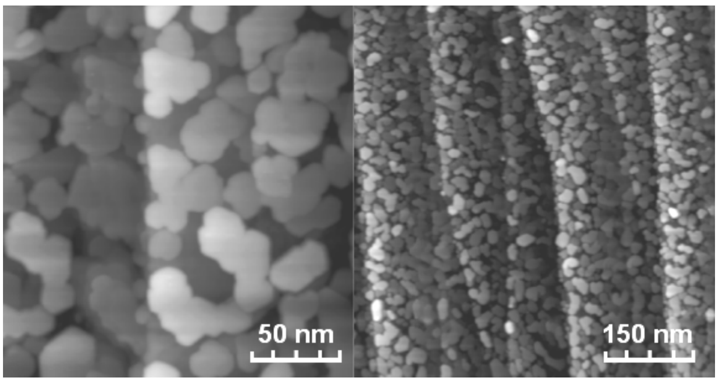

Fig. 1. STM topography images observed for 10 ML Ag deposited at RT on Si(111)-(7×7) substrate (200 nm × 200 nm on left and 500 nm × 500 nm on right), taken with the sample bias of V_T = +2.1 V and tunneling current of I_T = 0.5 nA.

As a result of the reduction of the island dimension (in z direction) only the standing wave states are allowed to exist. Thus one dimensional energy spectra (in z direction) consist of discrete energy states separated by an energy gap of the characteristic width. The basic physics of a quantum well is based on the model of a particle confined in a potential well with infinite potential barriers separated by a small distance of H_N [8]. The wavefunction describing the particle entrapped in quantum well is a set of standing waves:

$$\Psi = \sin \frac{n\pi z}{H_N} \Phi(x, y) \tag{1}$$

and the energy is a set of sub-bands separated by a discrete transverse component:

$$E_{\perp}^{n} = \frac{\hbar^2 n^2 \pi^2}{2 m_{\perp}^{*} H_N^2} \tag{2}$$

where n is an integer, $\hbar$ is the Planck constant, and $m_{\perp}^{*}$ is the effective mass for the transverse motion of the electron. Supposing that $E(k_x, k_y)$ associated with the in-plane wavefunction $\Phi(x, y)$ is small compared with $E_{\perp}^{n}$, each sub-band of energy is associated with n-th quantum state. For the case of simple metal, the total number of quantum states in a partially filled conduction band is equal to the number of atomic layers N, and the energy separation between two successive quantum states near to the Fermi level is a function of island thickness H_N:

$$\Delta E = \frac{\pi \hbar V_F}{H_N} \tag{3}$$

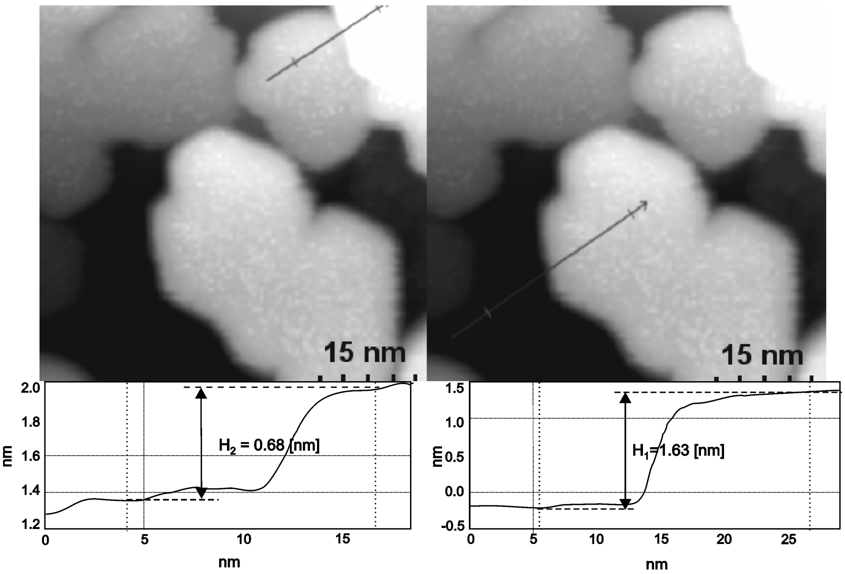

Fig. 2. Topography images (50 nm × 50 nm) of Si substrate covered with Ag islands of different heights. The measured relative heights of Ag islands: H_1 = 1.63 nm and H_2 = 0.68 nm refer to islands thickness of about 7 ML and 10 ML accordingly

where H_N is the thickness of the islands consisting of N atomic monolayers, and V_F is the Fermi velocity (1.39×10^6 m/s for Ag). Thus the electronic properties of an island should be directly correlated to its thickness.

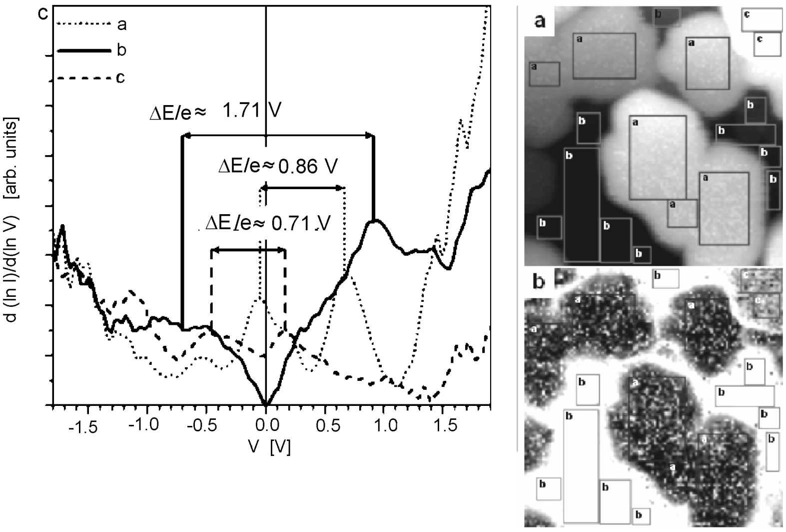

Fig. 3. STM/STS measurements for islands of different heights: a) Topography image of the same area as in Fig. 2. b) Tunnel current map (CITS) measured at the same spot of the sample acquired at $V_T = 0.1$ V. c) Dynamic conductance d(ln$I$)/d(ln$U$) curves measured on the island of 7 ML (a), 10 ML (c) and Ag coated background (b). Appropriate upright lines mark the onsets of HOS and LUS. Distances between marked peaks indicate values of energy separation of HOS and LUS for areas of different heights

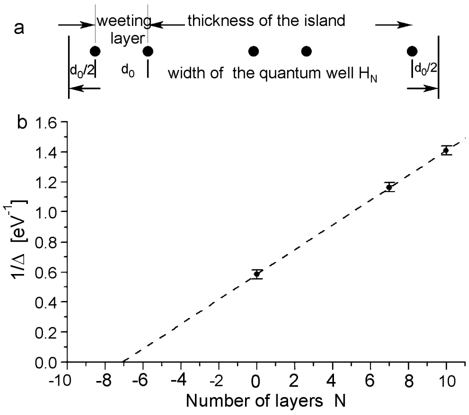

Fig. 4. a) A model of actual width of the quantum well [1] (description in the text). b) The inverse of energy separation between the HOS and the LUS as a function of the island thickness

Simultaneous topographic and spectroscopic measurements were carried out over the flattop islands of different heights of 7 ML, and 10 ML in relation to Ag coated background (Fig. 2). Characteristic peaks were expected to be observed in normalized differential conductivity spectra d(ln$I$)/d(ln$V$) *vs.* V (bias polarization), which should correspond to a stepwise increase of the density of states with the energy. Figure 3 displays d(ln*I*)/d(ln*V*) curves taken on the islands of 7 ML and 10 ML heights, and on the apparent background (also Ag island). Each spectrum revealed the characteristic peaks which can be referred to the two successive energetic states close to the Fermi level: the highest occupied subbands (HOS) (on the right) and the lowest unoccupied subbands (LUS) (on the left). The energy separation ΔE between HOS and LUS is a function of the island thickness H_N according to the formula (3). A simple model [1] was used to estimate the total width of the quantum well (Fig. 4a). This model includes the width of Ag wetting layer and the length of the electron wave decay on both sides of the quantum well (where d_0 = 0.24 nm is the Ag interface spacing). Figure 4b shows the inverse of energy separation ($1/\Delta E$) between HOS and LUS energies as a function of the island thickness. The extrapolated line intersects the thickness axis at –7 (layers). This fact indicates that the observed islands are located on a thin Ag film consisting of 5 ML of Ag. Therefore, the actual thickness of the quantum well includes Ag wetting layer [9] (d_0), value d_0 related to the electron wave decay on both sides of the quantum well, the measured thickness of the *N*-layer island and the additional thin Ag film ($5d_0$) (seen as the black background in STM images).

4. CONCLUSIONS

Summarizing the work, Ag islands of different heights were observed on Si(111)-(7×7) substrate after deposition of about 10 ML of Ag. Surfaces of the islands were atomically flat. Ag islands revealed quantum size effects which were investigated by means of STM/STS technique. Values of energy separation between HOS and LUS were measured for individual islands, and compared with the theoretically calculated values. We estimated the total width of the quantum wells as 7, 14 and 17 ML and the measured values of energy separation were close to the expected 1.71 eV, 0.86 eV, and 0.71 eV respectively. This work can be used as starting point to study other characteristics which depend on the electronic structure of particular nanostructures.-

Acknowledgements

As regards Polish co-authors, this work was done under KBN – 2 P03B 042 25 Project.

References

[1] W. B. Su, S. H. Chang, W. B. Jian, C. S. Chang, L. J. Chen, and Tien T. Tsong, Phys. Rev. Lett., **86**, 5116 (2001).
[2] R. Wilkins, E. Ben-Jacob, and R. Jaklevic, Phys. Rev. Lett. **63**, 801 (1989).
[3] W. B. Sandomirski, Zh. Eksp. Teor. Fiz. **52**, 158 (1967).
[4] H. Hoffmann, *Festkörperprobleme*, ed. P. Grosse (Vieweg Braunschweig) vol. **XXII**, 255 (1982).
[5] A. D. Yoffe, Adv. in Phys. **42**(2), 173 (1993).
[6] R. C. Jaklevic and J. Lambe, PRB **12**(10), 4146, (1975).
[7] A. L. Wachs, A. P. Shapiro, T. C. Hsieh, and T.-C. Chiang, Phys. Rev. B **33**(2), 1460 (1986).
[8] D. Chen, J. Electron Spectrosc. Relat. Ph. **109**, 85 (2000).
[9] P. Sobotník, I. Ošt'ádal, J. Mysliveček, T. Jarolímek, and F. Lavický, Surf. Sci. **482-485**, 797 (2001).