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論　文　内　容　の　要　旨

氏　名　（　曲 章　）	
論文題名	Study of atomic surface potential on Si(111)-7×7 surface by high-frequency heterodyne-Kelvin probe force microscopy (高周波テロダイン・ケルビンプローブフォース顕微鏡によるSi(111)-7×7表面の原子表面電位の研究)

論文内容の要旨

The surface potential provides valuable information about the charge distribution and surface state on the semiconductor surfaces, which effect the reliability and stability of devices. Kelvin probe force microscopy (KPFM) is a technique that can measure the surface potential at semiconductor surfaces and interfaces with high spatial resolution. In general, the surface potential measured by KPFM is affected by the frequency dependent charge trapping on the surface/interface state of semiconductor surfaces. Therein a high-frequency heterodyne-KPFM method was proposed in our group, which can reduce the surface charge trapping influence.

In this thesis, to evaluate the surface potential correctly, I set up and used a high-frequency heterodyne-KPFM (HF-he-KPFM) method to measure the Si(111)- 7×7 surface at 78 K. In addition, the atomic structure and electrostatic properties on Co/Si(111)-7×7 were identified by noncontact atomic force microscopy (NC-AFM)/KPFM at 78K. Furthermore, the semiconductor properties of Co ring-like clusters on Si(111) surface was observed by Kelvin probe force spectroscopy (KPFS).

In chapter 1～3, the research background and purpose of this paper were described. The principles of AFM and KPFM are introduced.

In chapter 4, the experimental equipment of AFM/KPFM was described in detail. Mainly cover the tip, sample, and the control system of AFM/KPFM/HF-he-KPFM.

In chapter 5, atomic structure and electron distribution of Co atoms adsorbed on Si(111) surface was investigated by NC-AFM/KPFM at 78 K. The Co atoms in the initial adsorption were distinguished from defects on the surface by line profile analysis and force spectroscopy. For the first time, Co clusters and the V_{LCPD} was measured by NC-AFM/KPFM. Each Co cluster was found to have a ring-like structure after annealing a sample at 230℃, and its bond energy is lower than that of a Si adatom owing to the passivated dangling bonds. I proposed a structure model to explain the atomic structure including three subsurface Co atoms and six Si adatoms. DFT calculations with the GGA mode were carried out to optimize the structure model and simulate the local surface potential distribution of ring-like Co cluster on Si(111)-7×7 surface.

In chapter 6, I investigated the physical properties of Co ring-like clusters reconstruction with a low Co coverage on a Si(111)-7×7 surface with atomic resolution by AFM/KPFM at 78 K. I compared the applied bias dependence of frequency shift between two types of structure: Si(111)-7×7 and Co ring-like clusters reconstruction. As a result, the accumulation, depletion, and reversion layers were identified in the Co ring-like clusters reconstruction by bias spectroscopy. For the first time, I found that Co ring-like clusters reconstruction on the Si(111)-7×7 surface shows semiconductor properties by KPFS.

In chapter 7, I presented the high-low KPFM study on n-type Si (111)-7×7 surfaces. By comparing V_{CPD} images by conventional KPFM and HF-he-KPFM, I found that frequency dependence of carrier emission and capture of surface states. The HF-he-KPFM can more accurate to measure the surface potential. Additionally, the electric field effect of two methods was analyzed, and the $\partial C/\partial V$ information was revealed by the high-frequency KPFS. This result shows that HF-he-KPFM is a promising method to study semiconductor properties more accurately and is an important complementary tool for understanding semiconductor materials.

In chapter 8, the conclusions of this study and future prospects were discussed.

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論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

The surface potential provides valuable information about the charge distribution and surface state on the semiconductor surfaces, which effect the reliability and stability of devices. In general, the surface potential measured by Kelvin probe force microscopy (KPFM) is affected by the frequency dependent charge trapping on the surface/interface state of semiconductor surfaces. This dissertation summarizes the achievements of the research on (1) identification of the atomic structure and electrostatic properties of Co/Si(111) surface, (2) measurement of the semiconductor properties of Co ring-shaped clusters on Si(111) surface by low frequency Kelvin probe force spectroscopy (KPFS) and (3) evaluation of the surface potential on Si(111) surface at 78K by a high-frequency heterodyne-KPFM method. The main findings in the thesis are summarized as follows.

First, the atomic structure and electron distribution of Co atoms adsorbed on Si(111) surface was investigated by non-contact atomic force microscopy (NC-AFM) /KPFM at 78K. The Co atoms in the initial adsorption were distinguished from defects on the surface by line profile analysis and force spectroscopy. For the first time, Co clusters and the V_{LCPD} was measured by NC-AFM/KPFM. Each Co cluster was found to have a ring-like structure after annealing a sample at 230℃, and its bond energy is lower than that of a Si adatom owing to the passivated dangling bonds. The structure model to explain the atomic structure including three subsurface Co atoms and six Si adatoms was proposed. Density functional theory (DFT) calculations were carried out to optimize the structure model and simulate the local surface potential distribution of ring-like Co cluster on Si(111)-7×7 surface.

Second, the physical properties of Co ring-like clusters reconstruction with a low Co coverage on a Si(111) surface with atomic resolution was investigated by AFM/KPFM at 78K. The applied bias dependence of frequency shift between Si(111) and Co ring-like clusters reconstruction were compared. As a result, the accumulation, depletion, and reversion layers were identified in the Co ring-like clusters reconstruction by low frequency KPFS. For the first time, Co ring-like clusters reconstruction on the Si(111) surface was found as semiconductor properties.

Finally, the high-frequency heterodyne-KPFM method was set up and local contact potential difference (V_{LCPD}) images were compared by conventional low-frequency KPFM and high-frequency heterodyne-KPFM. It was found that frequency dependence of carrier emission and capture of surface states. Additionally, the electric field effect of two methods was analyzed, and the capacitance gradient with respect to bias voltage ($\partial C/\partial V$) information was revealed by the high-frequency KPFS. This result shows that high-frequency heterodyne-KPFM is a promising method to study semiconductor properties more accurately and is an important complementary tool for understanding semiconductor materials.

As mentioned above, this thesis is a new study on atomic surface potentials and other aspects on Si(111) surface by high-frequency heterodyne-KPFM. The findings are useful not only for a fundamental but also application, and contribute significantly to applied physics, especially in the field of semiconductor devices. Therefore, this thesis is judged valuable as a doctoral thesis.