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主　論　文　の　要　旨

論文題目　A Study on Characterization of One-dimensional Semiconductor Nanomaterials by Microwave Atomic Force Microscopy
(マイクロ波原子間力顕微鏡による一次元半導体ナノ材料の評価に関する研究)

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論　文　内　容　の　要　旨

In recent years, the continuous advances of nanotechnology lead to the synthesis and characterization of one-dimensional semiconductor nanomaterials. The enhanced unique electrical properties of one-dimensional semiconductor nanomaterials caused by their unique geometry with high aspect ratio arguably determine their applications in electronics devices, gas sensors and chemical sensors. To characterize the vital local electrical properties of nanomaterials, atomic force microscope (AFM) based techniques including scanning kelvin probe microscopy (SKPM), electrostatic force microscopy (EFM), and microwave impedance microscopy (MIM) are springing up accordingly. However, there are several unresolved issues in the current AFM based techniques.

Firstly, they work in contact or tapping mode, which could damage the sample. Secondly, an additional signal has to be added to the sample which results in not only a difficulty to measure the local electrical property quantitatively but also a decrease of spatial resolution. In order to solve these issues, microwave atomic force microscopy (M-AFM) that works in a non-contact and non-destructive with nanoscale resolution was introduced in this study. To precisely evaluate the local electrical properties of nanomaterials and nanomaterial devices, this study not only considered the evaluation method and accuracy of M-AFM, but also investigated the interaction between the evaluated sample and M-AFM probe. Specifically, the influence of the microwave on the electrical properties of nanomaterial was analyzed. Meanwhile, the influence of electrical field of the measured nanomaterial devices on M-AFM evaluation results was also investigated. Finally, this study successfully established the measurement method which can evaluate the relative permittivity of one-dimensional nanomaterials and the electrical conductivity of the one-dimensional nanomaterial-based devices. This thesis mainly consisted of five chapters.

Chapter 1 introduced the background and the objectives of this study. Specifically, the significance of local electrical property evaluation, the issues of local electrical property evaluation based on AFM technique and the development of M-AFM were respectively described.

In Chapter 2, the principles of AFM and microwave measurement system of M-AFM were respectively introduced. In particular, the working principle of M-AFM and the mechanism of the microwave measurement based on M-AFM were introduced. Next, the fabrication of M-AFM probe was introduced. In order to evaluate the fabricated probes, the experiment was carried out with a sample consisted with Au film and Si substrate. The evaluated results measured by M-AFM demonstrated that the fabricated M-AFM probes can precisely evaluate the topography and microwave image on the nanometer scale.

Chapter 3 chiefly focused on the quantitative characterization of the local relative permittivity on the nanometer scale. Based on the force curve measurement method and the additional atomic force caused by microwave between M-AFM probe and sample, a novel analytical method and evaluation equation used to evaluate the local relative permittivity of one-dimensional nanomaterials were proposed. One reference material was used for calibration and the relative permittivity of each kind of nanomaterials were evaluated respectively. The quantitative evaluation of nanomaterial's local relative permittivity was realized based on the change of force curve caused by microwave. The results demonstrated that M-AFM can be used to precisely evaluate not only the local relative permittivity of nanomaterials, but also the distribution of the relative permittivity of one-dimensional nanomaterials.

In Chapter 4, the electrical conductivity of SnO_2 nanobelt field effect transistor (FET) was successfully evaluated by M-AFM. First of all, the SnO_2 nanobelt FET was fabricated. Secondly the output characteristic of the fabricated SnO_2 nanobelt FET and the average electrical conductivity were measured by a parametric test fixture. The output characteristic of the SnO_2 nanobelt FET indicates that the carrier density in the SnO_2 nanobelt can be accurately modulated by the gate voltage. Finally, M-AFM was utilized to measure the topography and reflected microwave images of the SnO_2 nanobelt FET under different gate-source voltages. Based on the microwave image, the local electrical conductivity of SnO_2 nanobelt under different gate-source voltages, which reflected the change of the carrier density in the nanobelt caused by the change of the gate voltage, was evaluated. M-AFM measured electrical conductivity of the SnO_2 nanobelt FET under different gate-source voltages demonstrated that M-AFM can be used to quantitatively evaluate the local electrical conductivity of one-dimensional nanomaterial devices thereby determining the carrier density at any local position on the nanomaterial of the devices.

Finally, the most significant achievements in this study were summarized and respectively discussed in Chapter 5.

To sum up, this study successfully evaluated the relative permittivity of semiconductor one-dimensional nanowires and the electrical conductivity of nanomaterial devices quantitatively in a non-contact mode and non-destructive fashion with nanoscale resolution utilizing M-AFM. This study successfully constructed an evaluation method for accurately evaluating the electrical properties of nanomaterials and nanomaterial-based devices.