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主論文の要旨

論文題目　**A Study on Quantitative Evaluation of Local Permittivity and Conductivity Using Microwave Atomic Force Microscope**

（マイクロ波原子間力顕微鏡を用いた局所誘電率と局所導電率の定量評価に関する研究）

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論文内容の要旨

Atomic force microscopy (AFM), one of the most popular scanning probe microscopies, has been a powerful surface detection instrument with nanoscale since its invention. With the development of nanotechnology and molecular biology, rapid, non-destructive measurement methods for various physical properties of nanomaterials and cells have become essential. Therefore, as an excellent measurement platform which has diverse measurement environments and evaluable materials, AFM has been integrated with different measurement techniques. For electrical property, although various functional AFMs have been developed, non-contact quantitative evaluation for intrinsic local permittivity and conductivity of materials has always been an issue. On the other hand, microwave is an ideal non-contact measurement method for conductivity and permittivity. Therefore, microwave atomic force microscopy (M-AFM) has been developed for local quantitative measurement of electrical properties. Although it successfully measured the local conductivity of two-dimensional metallic nanomaterials in non-contact mode, to apply it to dielectric materials and one-dimensional nanomaterials, it faces a challenge that the microwave in near-field region has a spatial distribution, which depends on the tip-sample distance and surface shape of the materials, thereby the accuracy of quantitative evaluation may be affected.

In this thesis, the author aimed at the expansion of the application of M-AFM and establishment of a theoretical framework for quantitative evaluation. The evaluation method for permittivity of dielectric materials and conductivity of metallic nanowires were developed for M-AFM. As the theoretical basis of quantitative evaluation, the spatial distribution of electric field between tip and sample was analyzed for both dielectric and metallic materials using near-field approximation. The validity of this theoretical model was investigated by simulation of finite element method (FEM). The details are as follows:

Chapter 1 introduces the background of this thesis. It includes the development overview of AFM, the measurement principle of AFM, the introduction about functional AFM for electrical property evaluation, the achievement and challenge of M-AFM and the objective of this thesis.

Chapter 2 is about the experiment approach of this study. The fabrication of two kinds of M-AFM probes using photo lithography and wet etching, electron beam (EB) evaporation and focus ion beam (FIB) etching were introduced. The performances of them were compared. The two probes were used for the measurement of dielectric materials and metallic materials, respectively, based on their features. The most suitable measurement modes of dielectric materials and metallic materials were also discussed.

In Chapter 3 the development of a quantitative evaluation method for dielectric materials is reported. The electrical interaction caused by microwave was analyzed and an analytical expression was derived for quantitative evaluation. In experiment, the force curves of Si, Al_2O_3, Ge and ZrO_2 samples with and without microwave were measured under non-contact mode. The variation of force caused by microwave was extracted and the local permittivity of these materials were quantitatively determined based on the analytical expressions.

In Chapter 4, on the other hand, the quantitative evaluation method for conductivity was improved for metallic nanowire samples based on a semi-near-field model. A semi-near-field model combining the law of microwave reflection and near field approximation was set up as the improvement of traditional plane wave model. The non-contact microwave image of Al, Ag and Cu nanowire were measured on a Pt substrate with Au strips, which was designed to contribute to calibration and thus made it possible to achieve the evaluation within one scanning. Similarly, we also demonstrated that the quantitative evaluation of conductivity of metallic nanowires were successfully realized using semi-near-field model.

Chapter 5 mainly focused on the simulation study of the field distribution of M-AFM probes using finite element method (FEM). In order to describe the field distribution of the microwave between probe and sample, a refined model with near field approximation was proposed. Based on this theoretical model, the incident waves emitted from a slit probe and a coaxial probe were calculated and compared to their simulation results to verify the near-filed model. In addition, the effect of structure parameters of the two probes on microwave emission were also studied by FEM simulation in order to determine the optimal design of the probes. To demonstrate the validity of near field model for quantitative evaluation, the slit probe was simulated with different dielectric samples, and the results were found to correspond to near field model rather than plane wave model.

Finally, in Chapter 6 we summarize the work of this study. In conclusions, according to the different requirements, the evaluation of dielectric materials is based on force curve measurement using a slit probe, and metallic nanowires are evaluated through the surface reflection of microwave using a coaxial probe. The spatial distribution of electric field between tip and sample can be described by near-field model, and the validity of the model has been demonstrated by FEM simulation. Through this research, M-AFM is proved to be a promising non-contact quantitative measurement instrument for determining local permittivity and conductivity of dielectric and metallic materials.