Multiple-Probe Scanning Probe Microscopes: Characterization of Nanoarchitectonic Neuromorphic Systems

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We have developed multiple-probe scanning probe microscopes (MP-SPMs) which is not only useful in revealing physical properties of individual nanostructures and nanomaterials but also in investigating nanoarchitectonically assembled nanosystems. In this seminar, as an example, I discuss about a study on complex networks of nanowires exhibiting interesting features such as a "small-world" property and 1/f behaviour. This study leads us to discuss about brain-type computation using nanoarchitectonic neuromorphic systems.

Characterization of individual nanomaterials has been extensively studied for future applications of nanomaterials. However, such characterization is, in many cases, still challenging. When lithographically-prepared electrodes are connected to a nano-object of interest, the required lithographic processes and even the observation of the object itself often cause serious damage and change physical properties of the object. MP-SPMs [1] not only realize characterization at the nanoscale without such lithographic processes [2,3] but also provide a variety of combinations of probe microscopies and spectroscopies [4]. In this paper, we present MP-SPM measurements on one- and two-dimensional nanomaterials and our MP-SPM experiments on nanoarchitectonic neuromorphic systems [5] formed by nanowires. Then, we discuss about physical properties of such complex networks; small-world feature and 1/f behavior.

The MP-SPMs used in this study are home-built systems which equip independently-driven four AFM/STM probes (see a left panel of Fig. 1). Each probe can be assigned to be an atomic force microscope (AFM) probe, a Kelvin force microscope (KFM) probe or a scanning tunnelling microscope (STM) probe depending on a type of required measurements. For example, all the four probes were operated in non-contact AFM mode to identify and control their locations with respect to a position of the nano-object, then two of them were in contact with the object as source and drain electrodes while the other two probes as electrodes for measuring potential variation in the region of interest (see a right panel of Fig. 1).

Samples were prepared on insulating substrates such as glass, mica, or SiO$_2$ on Si. For example, complex network conductors made of conductive peptide nanofibers, doped poly-aniline nanowires (see Fig. 1) and sliver (Ag) nanowires were synthesized by wet-chemical methods and drop-casted or spin-coated onto insulating substrates. Then, we used MP-SPM and other microscopes, and semiconductor

Fig. 1. Structure of MP-SPM and measurements using 4 probes with nanoscale precision are schematically illustrated.
parameter analyzers for characterizing and monitoring morphological and electrical properties of the complex networks. In our MP-SPM measurements, tuning fork type sensors having electrochemically etched tungsten tips [6] were used.

When we measure resistances of continuum 1D and 2D materials using two probes, measured resistances must be linearly and logarithmically proportional to the distance between the two probes, respectively. However, in the case of a complex pseudo-2D network comprising of doped-polyaniline nanowires [Fig. 2(a)], we found that the resistance between two probes did not show such a simple dependence as described above as confirmed by MP-SPM measurements. The result is rather well-explained by a non-trivial topological feature, in consistent with the concept of “small-world” property discovered by Watts and Strogatz [7]. The small-world feature appearing in complex nanowire networks further motivated us to investigate the dynamics of the complex networks which is known as 1/f fluctuation or 1/f noise. Figure 2(b) is an example of complex network formed by Ag nanowires each of which is covered by thin insulating polymer layer. This network shows interesting switching phenomena and dynamic fluctuation of current paths, resulting in 1/f behavior in power density spectra of transmitted electrical current.

MP-SPMs have been developed and applied to various type of measurements so far. The local and extended scale measurements with nanoscale input/output terminals are useful in revealing properties of individual nanomaterials and emerging function of nanosystems. In this paper, we presented the case of complex networks which are, in the other words, nanoarchitectonics neuromorphic systems. Further investigation will enable us to design and control dynamic properties of neuromorphic nanosystems for future brain-type computation using nanomaterials.

References


