

08-05 Magnetic resonance of a single nanoparticle. Sample preparation

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One of the open questions in nano-magnetism is related to the study of correlation between structural and magnetic properties of a single nanoparticle. Nowadays, the structural characterization with an atomic resolution is routinely possible due to the progress in electron microscopy. On the other hand, because of the limited magnetic sensitivity of conventional characterization techniques, most of the experimental studies have been carried out on large ensembles of particles, where distributions of particle sizes, shapes, orientations and chemical compositions make the interpretation difficult. Recently, a few studies related to the measurements of the magnetization of a single particle have been carried out using ballistic Hall magnetometry [1, 2], giant magnetoresistance effect [3], and micro-SQUID technique [4-6]. New techniques for single particle measurements, such as a carbon nanotube (CNT) SQUID [7], nanoscale SQUID [8], and CNT-based electromechanical resonator [9] have been reported, although quantitative analysis of the shape and size dependence of the nanoparticle magnetization or their dynamic properties has not yet been demonstrated by these technique.

We develop the novel technique for magnetic resonance measurements of a single nanoparticle. It was shown that the sensitivity of the bolometer technique should be sufficient to detect the magnetic resonance in a single nanoparticle [10, 11]. Even though the technique is rather challenging, the principle of detection remains simple. In this method, the absorption of the electromagnetic energy by resonant spins is detected by a rise in the temperature of the sample. The temperature-change can be detected by measuring the resistivity-change of a wire attached to the sample which is called a bolometer. Thus, in the method described, we will register the resistance change of the bolometer which in the ideal case is proportional to the temperature-change of the sample and the absorbed power, as schematically shown in Fig. 1.

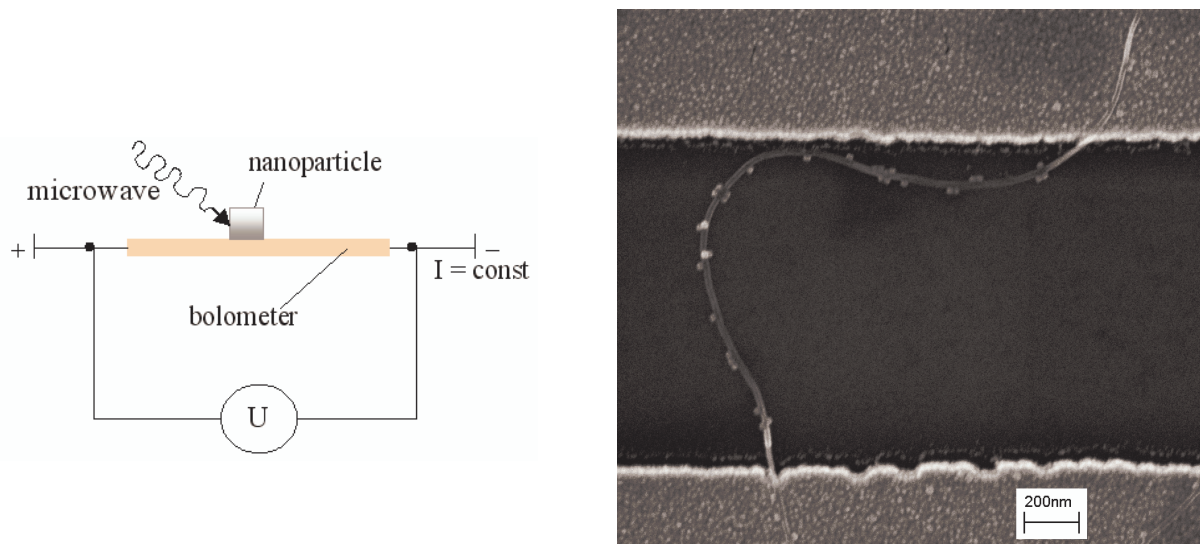


Fig. 1. Scheme of a bolometer detection using 4-point dc resistance measurements (left) and SEM image of an individual multi wall nanotube electrically contacted to two Au electrodes (right). Fe/FeO nanocubes (light spots) are adsorbed to the surface of the CNT.

We propose to use a carbon nanotube as a bolometer. According to our calculations and the preliminary work done to evaluate the sensitivity of the detection method, and also taking into

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account the well-known temperature dependence of the resistivity of CNTs [12], it is feasible to detect magnetic resonance from a nanoparticle with a size of 10-50 nm.

Recently, we have developed an experimental technique allowing the attachment of Fe/FeO nanoparticles to the surface of an individual CNT. The method involves dispersing the CNTs (both single wall (SW) and multi wall (MW) CNTs were used), adsorption of the Fe/FeO nanocubes on the surface of CNTs, nanomanipulation and electrical contacting of a CNT. The Fe/FeO nanocubes were earlier characterized by SQUID magnetometry, conventional FMR [13] and TEM [14]. The following methods were used to align a CNT on metallic electrodes (Au or Pt) which were patterned on GaAs or Si/SiO₂ substrates by electron beam lithography:

- nanomanipulation [15],
- dielectrophoresis technique [16, 17],
- wet deposition, *i.e.* spreading a droplet of a CNT dispersion onto electrodes.

Using the nanomanipulator a single CNT can be picked up from a TEM grid and positioned on the metallic electrodes. The manipulator is mounted inside the SEM chamber to control the positioning. This method allowed us to prepare a single MWCNT electrically contacted to four Pt tapered electrodes and fixed with tungsten deposited on the area of contacts between Pt electrodes and the CNT. I-V characteristics of such structure showed the ohmic behavior and a contact resistance of $\sim 100 \Omega$. (The contact resistance has been determined by comparing 2-terminal and 4-terminal resistances.)

Using the dielectrophoresis technique, *i.e.* the movement of polarizable objects in nonuniform ac electric fields, one can manipulate and align SW and MW CNTs between macroscopic electrodes as well as separate semiconducting and metallic CNTs. Using this method, we succeeded in alignment of small bundles of SWCNTs with attached magnetic nanocubes. However, alignment of individual SWCNTs still remains challenging.

In the third method, a specially designed array of grid-like electrodes (Au) together with their bonding pads was patterned onto a piece of thermally oxidized Si. A droplet of a strongly diluted dispersion of CNTs was deposited onto the structure and potentially well-aligned with the respect of electrodes CNTs were identified using SEM. Tungsten contacts were then deposited to fix ends of the CNT to Au electrodes. This method gave us the best yield of working devices in relatively short period of time: we were able to prepare 8 electrically contacted devices (individual MWCNTs with nanoparticles) on one substrate (see Fig. 1, right panel).

Currently we carry out I-V curve measurements of the obtained structures. Magnetic resonance measurements on the same structures will be performed shortly.

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