Integrated Nanoprobe for Measuring Microscopic Electronic Properties

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Abstract

Nanotools for measuring the microscopic electronic properties of conductive materials have been developed. Nanoprobes were integrated on microcantilevers for scanning probe microscopy using nanofabrication technologies. The four-point nanoprobe enables us to measure microscopic properties without a complex lithographic process.

1. Introduction

Recent progress in the miniaturization of electronic devices has achieved very small devices with nanometer-sized dimensions, called nanodevices. A new measurement technology for the nanometer region, called nanometrology, is now urgently required for the further development and improvement of nanodevices. For instance, micro- and nano-order electrical conductance measurement techniques are especially needed for the polycrystal-based organic semiconductor devices that are expected to become next-generation electronic devices. So far, however, only very limited solutions for this measurement problem have been proposed. This situation is an obstacle to the development of future electronic devices.

The four-point-probe method is widely used for measuring the electrical conductance of conductive materials. In a four-point-probe measurement, four probes, aligned with the same pitch, make contact with a sample surface. The voltage between the two inner probes is measured under the condition of constant current between the two outer probes. Since the contact resistance between the probes and the sample is negligible in the four-point-probe configuration, the correct value of the sheet resistance of the sample can be measured.

The conventional four-point probe is a microprobe whose pitch between the probes is 1 mm in almost all instruments (**Fig. 1**). Since the minimum pitch of recently developed probes is 100 µm, it is impossible to measure the microscopic properties of conductive materials using current probes. Miniaturization of conventional probes is limited by the precision constraints of machine technology. The other problem with conventional probes is high load force. The surface area of the sample is destroyed by the contact force of the probes. This is a serious problem for the very thin films utilized in miniaturized electronic devices.

A new type of miniaturized four-point-probe system for measuring micro- and nano-order electrical properties is urgently required. Our group is developing various types of four-point nanoprobe systems, based on state-of-the-art lithography and related technologies that have been studied in NTT Basic Research Laboratories for a long time. We have already developed a four-point nanoprobe system with 500-nm-pitch metal electrodes [1] and another with 60-nm-pitch Si electrodes [2]. A four-point probe with carbon nanosprings [3] has also been developed. In this article, we describe two types of four-point nanoprobes.

2. Integrated nanotool based on SPM technology

The basis for the four-point nanoprobe is a Si microprobe for scanning probe microscopy (SPM), as shown in **Fig. 2**. The conventional probe has only one tip on a single cantilever. For the nanoprobe, electrical and mechanical systems are integrated in a

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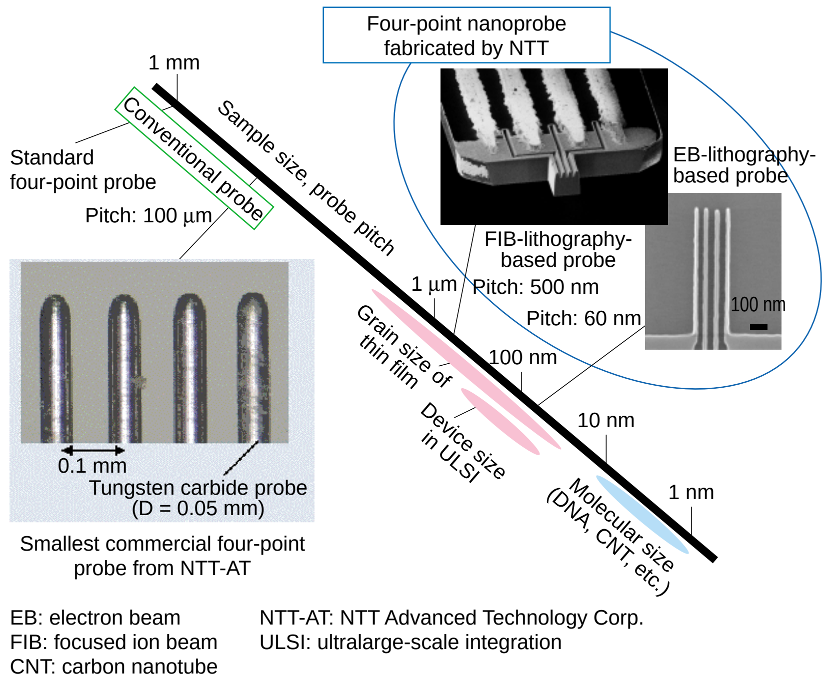


Fig. 1. Miniaturization of four-point probes.

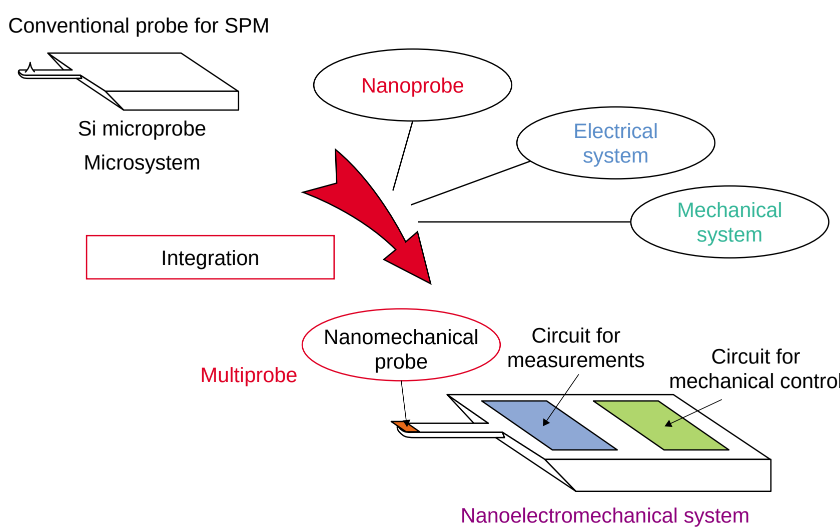


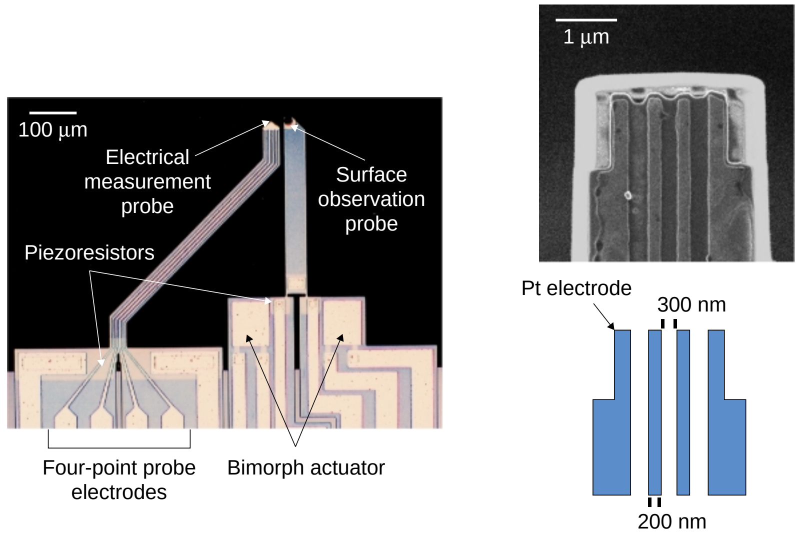
Fig. 2. Integrated nanotool.

microsystem to construct a nanoelectromechanical system. Lithographic techniques, such as electron beam lithography and ion beam lithography, are used to fabricate the nanoprobe on this nanotool. This integrated nanotool enables us to make a tiny, but highly functional measurement system.

Since the integrated nanotool is based on SPM technology, it easily achieves high resolution in a two-dimensional measurement. Furthermore, the contact force between the probes and the sample is low enough to avoid damaging the sample. These are the advantages of the integrated nanotool.

2.1 Four-point nanoprobe fabricated using nanolithographic technology

Figure 3 shows an example of an integrated nanotool [1] based on the concept shown in Fig. 2. This cantilever system has two levers. One (left) is for



(a) Overview of dual probe system (optical micrograph)

(b) Tip of electrical measurement probe

Fig. 3. Multifunctional integrated four-point nanoprobe.

electrical measurement with the four-point probes and the other (right) is for surface observation with a conventional SPM tip. The contact force between the sample and each probe is controlled independently using piezoresistors (electrical system) on the cantilever base operating in self-sensitive detection mode. The surface observation probe is removed in the vertical direction by a bimorph actuator (mechanical system) when the electrical measurement probe is in use. As shown in Fig. 3(b), the tip of the electrical measurement probe is a nanoprobe for four-point probe measurement. Four Pt nanoelectrodes 200-nm wide and with 500-nm pitch were fabricated by a nanolithographic technique using a focused ion beam (FIB). This dual cantilever system can be used in a commercial SPM system.

This dual cantilever system enabled the resistivity of the selected position in the topographic image taken by the surface observation lever to be measured by the electrical-measurement cantilever with high resolution. The feasibility of the electrical measurement was confirmed by measuring the contact characteristics using a flat conductive sample.

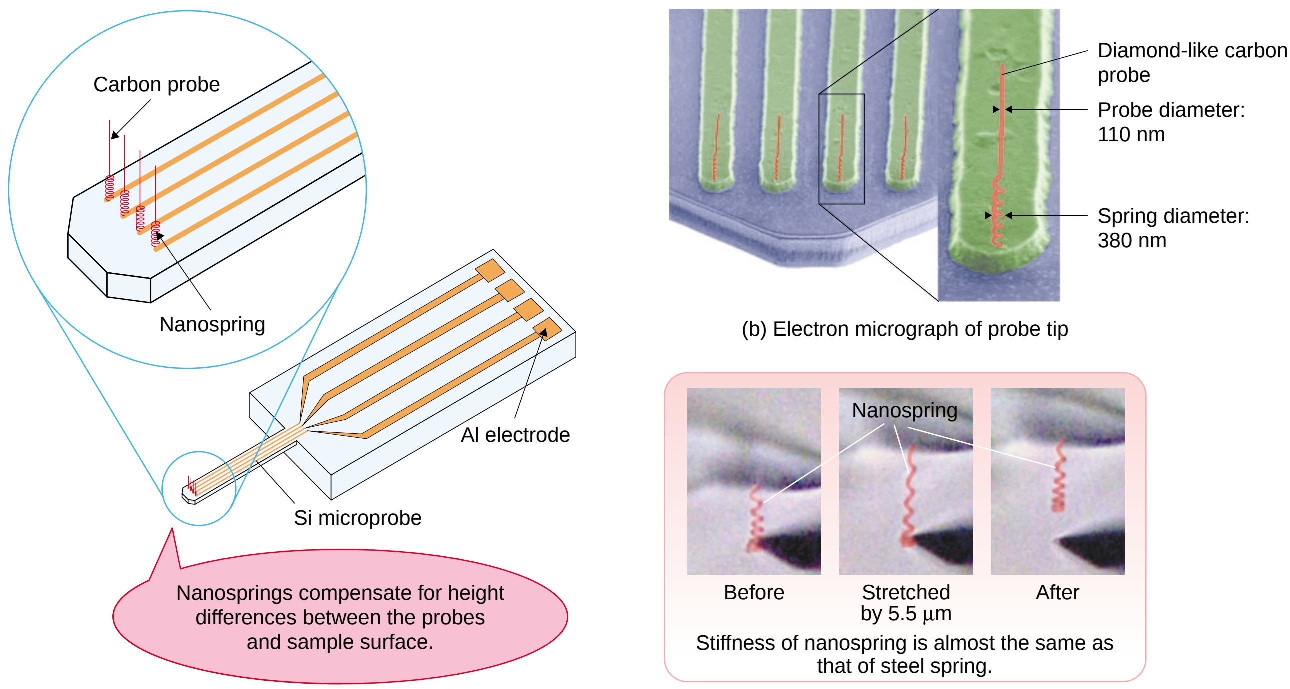
2.2 Four-point probe with nano-springs

The conventional four-point probe consists of four probes aligned with the same pitch (typically 1 mm). Mechanical springs are mounted at the root of each probe to maintain electrical contact between the probes and the sample. The springs compensate for the height differences of the contact point between the probes and the sample surface. Because it is very difficult to miniaturize the probes and springs using conventional machining technology, it had not been possible to reduce the distance between the probes.

Since the relative heights of the electrodes on the four-point probe described in the previous section cannot be changed independently, this system can be used only for flat surfaces. We plan to use nanofabrication technology to create a structure similar to the conventional four-point probe for the nano world.

Recently, various three-dimensional structures with spatial resolution in the nanometer range have been fabricated using the FIB deposition technique [4]. We integrated four carbon probes with nanosprings [3] on a Si cantilever with Al electrodes using FIB deposition, as shown in **Fig. 4**. The diameter of the carbon probe is 110 nm, and the diameter of the nanospring is 380 nm. The carbon probe made from diamond-like carbon (DLC) is electrically conductive and mechanically hard. These properties are desirable for the electrical probe.

The mechanical properties of the carbon spring were investigated using a spring with a 1300-nm diameter, as shown in Fig. 4(c). The length of the nanospring was expanded to 5.5 µm longer than its initial length which was about 11 µm. No distortion of the spring shape was observed after the experiment. In another experiment, measurements found the stiffness of the spring to be almost the same as



(a) Schematic of four-point probe

(b) Electron micrograph of probe tip

(c) Mechanical properties of nanospring

Fig. 4. Four-point probe with nanosprings.

that of the standard steel spring.

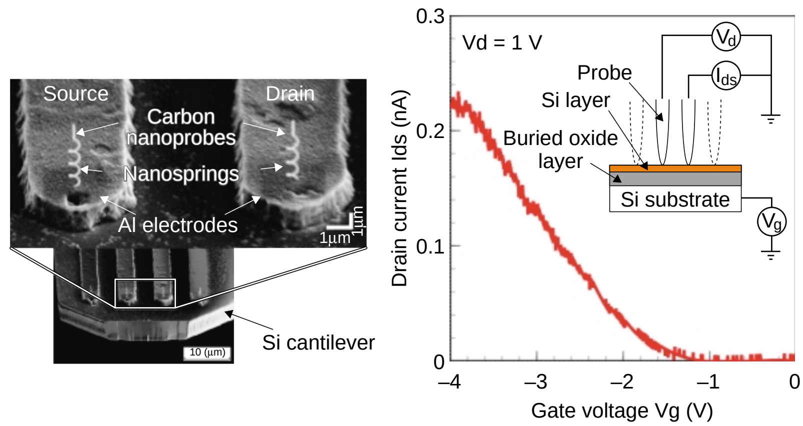
The probe heights in Fig. 4(b) are about 10 µm and they vary over a 200-nm range. The nanosprings compensate for the height differences. We confirmed that electrical contact between all four probes and the sample was established. This result shows that the nanosprings on the Si cantilever were actually acting as tiny mechanical devices.

3. Electrical measurement using the four-point nanoprobe

In measurements using the conventional four-point probe, damage to the sample surface cannot be avoided because high pressure is applied to the sample. The impact of this damage is not negligible for a very thin film or mechanically fragile film.

In our multiprobe on the SPM cantilever, the contact force between the sample and probe is controlled at very low pressures by the SPM system. The feasibility of the multiprobe with nanosprings was confirmed for the measurement of the field-effect transistor (FET) characteristics of a very thin Si layer. Three electrodes—gate, source, and drain—are required to measure the FET characteristics of semiconductor materials. In the experiment, two probes on the Si cantilever were used as the source and drain electrodes of a metal-oxide-semiconductor (MOS) FET, as shown in **Fig. 5(a)**. The buried oxide layer in the silicon-on-insulator (SOI) substrate acted as a gate oxide. The MOS-FET characteristics of the ultra-thin (10 nm) Si layer on SOI were successfully measured using the four-point nanoprobe on a Si cantilever [5]. As shown in Fig. 5(b), the conductance of the Si layer was controlled by the gate voltage applied to the Si substrate. Complicated procedures with a number of lithographic processes are required to measure FET characteristics in conventional methods. The four-point nanoprobe eliminates the need for time-consuming processes such as a lithographic process in order to measure the FET characteristics of a semiconductor thin film on an insulator layer.

Optimization of the deposition conditions for thin film transistors, such as polysilicon and organic semiconductors, can be more easily achieved than with the conventional method. If we can make a probe smaller than a grain of a polycrystal material, we will be able to measure the conductance within one grain and the conductance across a grain boundary.



(a) Electron micrograph of FET probe

(b) Measured FET characteristics

Fig. 5. FET probe for semiconductor film.

4. Conclusion

Multiprobe systems are required for measuring of sheet resistance and electrical transport characteristics. A conventional SPM system with a single probe can measure only the contact characteristics between the probe and a sample. In this article, we described two kinds of four-point nanoprobes integrated on an SPM cantilever using a nanofabrication process, along with their application for electrical measurements. The first one is the four-point nanoprobe for electrical measurement with piezoresistors integrated on the dual cantilever system. Four Pt nanoelectrodes, 200 nm wide, were successfully fabricated on the tip of the cantilever by FIB nanolithography. The second is a set of carbon probes with nanosprings integrated on the Si cantilever. The height differences among the probes are compensated for by the nanosprings. The four-point probe with nanosprings can be used to measure the FET characteristics of a very thin Si film.

Four-point nanoprobes integrated on an SPM cantilever using a nanofabrication process will be useful in developing new semiconductor materials for future electronic devices. In the near future, nanoprobe distances will be reduced to less than 100 nm, which is the typical grain size of polycrystal films. Our final goal is to make a sub-10-nm gap electrode for measuring molecular devices.

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