A smart microfour-point probe with ultrasharp in-plane tips

Ji-Kwan Kim,[1] Yan Zhang,[1] and Dong-Weon Lee[2,a)]
[1]*MEMS and Nanotechnology Laboratory, Graduate School of Mechanical Engineering, Chonnam National University, 300 Youngbong, Buk, Gwangju 500-757, Republic of Korea*
[2]*MEMS and Nanotechnology Laboratory, School of Mechanical Systems Engineering, Chonnam National University, 300 Youngbong, Buk, Gwangju 500-757, Republic of Korea*

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We propose a smart microfour-point probe (μ4PP) with ultrasharp in-plane tips that are arranged in a square with a spacing of 20 μm. The μ4PP consists of a supporting cantilever and four subcantilevers. The subcantilevers are symmetrically suspended from the square frame at the end of the supporting cantilever. A thermal actuator based on the bimorph effect is also integrated on each subcantilever for functionalization of interest. The unique configuration of the four-terminal tips is very useful for versatile applications of the μ4PP. © *2009 American Institute of Physics.*
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A four-point probe (4PP) is a very simple approach for measuring sheet resistance in the condition of various geometries.[1–3] The most common methods are the collinear and the van der Pauw methods.[4] In the former case, current is passed between the two outer probes and the voltage is measured across the inner pair. To obtain the sheet resistance, the measured ratio of the voltage drop to the forced current is multiplied by a geometric correction factor that depends upon the probe geometry and the ratio of the probe-spacing to the thickness of the conductive region of the sample that is to be evaluated.[5,6] In the van der Pauw method, to improve the accuracy, the probe connections are rotated 90° and positioned on the circumference of the sample. Then, the average resistance is calculated through repeatedly measured data.

With the development of advanced techniques in semiconductors, ultrasmall electronic and mechanical devices have been built for large-scale integration and high performance. The analytical techniques for process control and characterization of these fabricated systems are quite important and difficult, challenging even, in the further scale-downed feature size, especially for the investigation of the properties of thin films. Several attempts that are based on silicon micromachining have been made to improve 4PP characteristics, including a reduction in its probe-to-probe spacing for further applications. Recently, various 4PPs have been fabricated by the means of photolithography for obtaining a higher spatial resolution.[7,8] If the distance is decreased, then the 4PP has the advantages of miniaturization of the device, the ability to yield more detailed measurements, and the reduction of damage to the substrate. Another advantage is a greater sensitivity to the surface layer, since the effective depth of probing in a homogeneous sample is approximately proportional to the interelectrode spacing. However, there is a fundamental limitation in reducing the spacing of probe tips because most of the micromachined tips for the 4PP applications are arranged in a row. Also, it is difficult to measure the electrical properties of the substrates with curved surfaces.

The main focus of this paper is the design and fabrication of smart micro-4PP (μ4PPs) for minimizing damage to samples and providing accurate measurements for small contact areas, especially for nanoscaled samples. A modified method is proposed for the fabrication of very sharp tips in plane. In addition, the proposed μ4PP can be employed as either a gripper or a microheater.

A schematic diagram of the proposed smart μ4PP design is shown in Fig. 1, with a close-up detail of the μ4PP. The device consists of a supporting cantilever and four subcantilevers with integrated thermal actuators. The four subcantilevers are arranged at the end of the supporting cantilever. The four subcantilevers that are symmetrically suspended from the square frame at the end of the supporting cantilever are the sensitive components and should be protected from destruction and other forms of contamination. Taking one of the subcantilevers for example, it consists of 3 μm thick silicon with 0.5 μm SiO_2 grown on, and is coated with a Au/Cr layer of 150/50 nm for the evaluation of electrical conduction. Each of the subcantilevers has dimensions of $l=140$ μm, $w=40$ μm, and $t=3$ μm, with the *V*-grooved patterns further reducing the stiffness for minimizing damage to the test sample of interest. The tip-spacing is about 20 μm and can be even less, depending upon the specific application.

Through the use of integrated actuators that are based on a bimorph effect, the designed μ4PP can be also used as a gripper, with four contact points for reliably holding or moving micro/nano-objects. The *V*-grooved pattern on each subcantilever is desired for a large thermal expansion of the metal layer, and is also flexible in accommodating various element geometries.[9] The small contact area enables the μ4PP to hold light objects with minimum damage to the material.

On the other hand, thermal heaters are formed by either lightly doped silicon or the deposition of metal on the top layer, as the thermal resistor is placed only at the end of the subcantilever. One of the probes can be used as a heater and

[a)]Author to whom correspondence should be addressed. Electronic mail: mems@chonnam.ac.kr. Tel.: +82 62 530 1684. FAX: +82 62 530 1689.

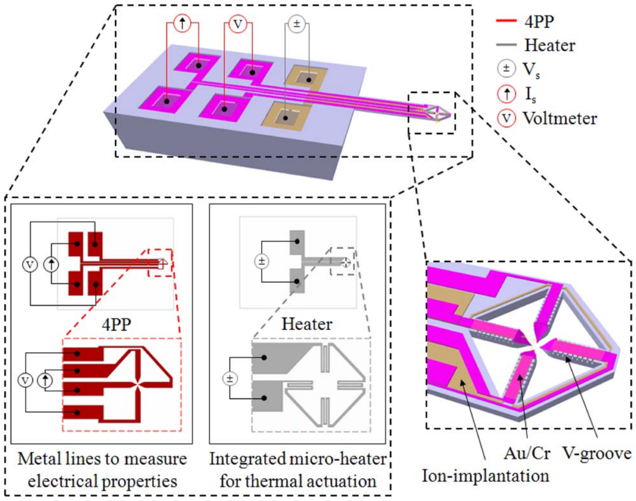

FIG. 1. (Color online) A schematic diagram of the smart μ4PP, with a close-up detail of the μ4PP.

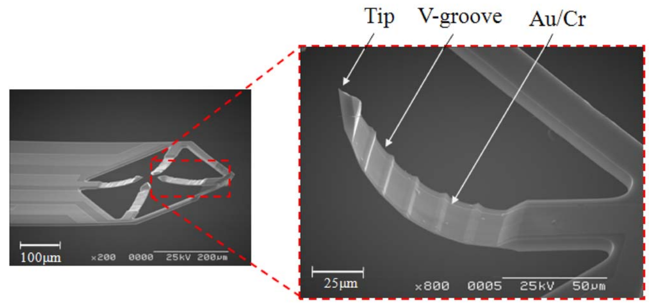

FIG. 3. (Color online) SEM images of the fabricated smart μ4PP.

the other probes can be employed for investigating the behavior of thermal transfer through the electronic method. Thermally induced expansion will lead to a little downward deflection, which can form a small angle between the heater and the sample. The sharp tip is desired for less damage and heating only small fragile elements. The test samples would also be designed to match the probes' configuration for a reliable and efficient testing process.

The μ4PP is fabricated by conventional microfabrication techniques. A 200 nm thick layer of SiO_2 is grown by wet oxidation on silicon-on-insulator (SOI) wafers. Then, a photoresist (AZ5214) is spun on top of the SiO_2 layer, and is exposed to UV light through a chromium (Cr) mask that defines the *V*-grooved pattern on the wafer. The *V*-grooved pattern is then etched in a trimethyl ammonium hydroxide solution at 80 °C. After the standard cleaning process, SiO_2 is grown again to pattern the cantilever and tip shapes. The shape of the in-plane tip is defined by photolithography. Then, the SiO_2 is wet-etched until the neck width of the base-shaped mask becomes zero. After the photoresist is removed in acetone, the silicon part is dry-etched by using a reactive-ion-etching system. Finally, the SiO_2 is removed in a solution of buffered hydrofluoric (HF) acid to define the configuration of the probes, as well as the ultrasharp in-plane tips modification. Figure 2 shows the optical and scanning electron microscope (SEM) images that are obtained during the in-plane tip fabrication. Reliable fabrication of the in-plane tips with a tip radius of curvature 10 nm is successfully confirmed through the experiments.

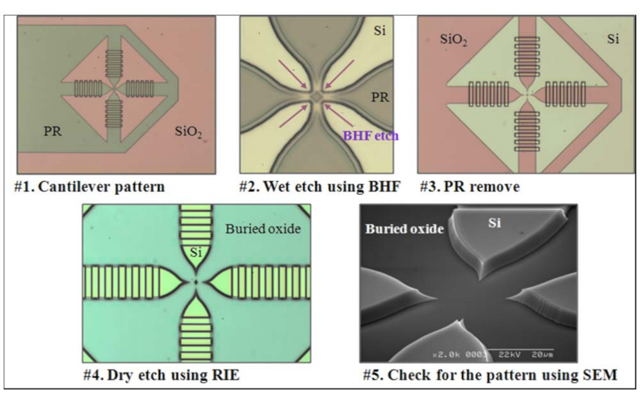

FIG. 2. (Color online) Fabrication procedures and a SEM image of the in-plane tip.

After a photolithography process with a thick photoresist, the wafer is subjected to boron ion implantation at a dose of 7×10^{14} ions/cm^{-2} and energy of 50 keV for the fabrication of the integrated heaters. The resulting shallow implant creates an asymmetrical piezoresistive region through the silicon film thickness. Subsequent rapid thermal annealing at 950 °C for 30 s activates the boron and limits diffusion of the active species. Following the implantation and activation, conventional micromachining techniques are employed for fabricating the rest of the μ4PP. The smart μ4PPs are finally released from the substrate by the removal of an intermediate oxide layer of the SOI wafer in buffered HF.

Figure 3 shows SEM images of the fabricated smart μ4PP. The subcantilever is initially curled by the thermal stress of a thin metal layer that is deposited on the subcantilevers by sputtering. The initial probe-to-probe spacing of the devices is about 20 μm and can be decreased to 500 nm by the use of either electron beam or ion-beam lithography. Further decrease in the initial distance is desired for samples with small contact areas.

To functionalize the fabricated μ4PP, electrical measurement systems are combined with micromanipulators. A current of 0.1–10 mA is applied to two outer electrodes, while the voltage difference is measured through the other electrodes. A constant current is applied in our experiments for minimizing the influence of contact resistance between the electrode tips and the sample surface. Figure 4 shows the experimental *I-V* relations of microparticles that are obtained from silver-based epoxy. The measured resistivity of the object is almost the same as the value provided by the manufacturer of the silver-based epoxy. Further optimization of the electrical readout system will increase the signal-to-noise ratio and allow a precise measurement of soft objects, such as thin organic semiconductors of biomaterials with even higher sheet resistance. The measured deflection of the subcantilevers at 25 mW actuation power is about 80 μm. The resulting switching speed of -10 ms can be achieved and the limitation of the switching speed is caused by a thermal response time of the subcantilevers.

In summary, we have proposed a smart μ4PP design that employs integrated thermal actuators for observing the physical properties of metals and semiconductors. Reliable fabrication for ultrasharp in-plane tips are also demonstrated

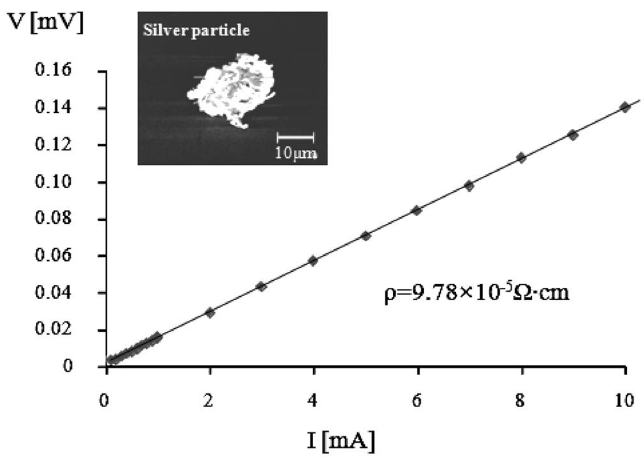

FIG. 4. Resistivity measurement by the use of the fabricated smart μ4PP.

by the use of a conventional photolithography. The configuration and modified sharp tips at the end of each subcantilever enable good conditions of contact for reducing damage in the interest of reliable electrical and thermal characterization. In addition, the smart μ4PP can be applied as a gripper that is based on thermal actuation and microheating. Both the material properties under variable conditions and the exact performance will be studied for practical functionality.

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