Micromachined piezoresistive proximal probe with integrated bimorph actuator for aligned single ion implantation

A. Persaud,[a] K. Ivanova, and Y. Sarov
Institute of Nanostructure Technologies and Analytics, University of Kassel, Kassel, Germany

Tzv. Ivanov, B. E. Volland, and I. W. Rangelow[b]
Technische Universität Ilmenau, Ilmenau, Germany

N. Nikolov
Microsystems Ltd., 9010 Varna, Bulgaria

T. Schenkel
E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720

V. Djakov and D. W. K. Jenkins
Central Microstructure Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, United Kingdom

J. Meijer and T. Vogel
RUBION, Ruhr-Universität Bochum, 44780 Bochum, Germany

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The authors report a microfabrication procedure of self-actuated piezoresistive scanning probes (SAPSPs). They are designed for a SAPSP instrument that is integrated with an ion beam for aligned single ion implantation in ultrahigh vacuum. The novelty of the design is an integrated hollow pyramid, instead of a previously mechanically hand mounted pyramid [J. Vac. Sci. Technol. B **23**, 2798 (2005)]. The pyramid has dual purpose. First it collimates the ion beam and suppresses secondary particles from the back side of the cantilever, so that secondary particles from the target material can be used for single ion detection. Second the pyramid also provides an atomic force microscope tip for the scanning probe. A crucial step in the fabrication is the back side opening via etching for the hollow pyramid. The fabrication procedure will be discussed in detail. [DOI: 10.1116/1.2375079]

I. INTRODUCTION

Since the size of semiconductor devices is still shrinking according to Moore's law, a point will be reached soon where the distribution of dopants within the semiconductor will become critical. Already effects of the Poissonian distribution due to the random implant in semiconductors have been reported.[1,2] By using a single ion implanter these critical effects can be explored and analyzed. Apart from the semiconductor industry new research fields will be accessible with a single ion implanter, for example, the realization of silicon based solid-state quantum computers.

The quantum computer can be seen as the ultimate limit of Moore's law where single atoms can form the basic units of computation. At these dimensions the laws of quantum mechanics come into play, which actually leads to a different kind of computation paradigm compared to classical computation. In a quantum computer the basic unit for computation is normally presented by a two level system, for example, the spin state of an electron. Many different possible realizations of a quantum computer have been suggested. A silicon solid-state quantum computer was first proposed by Kane.[3] It requires single phosphorus atoms placed in an ordered array in a silicon layer, aligned to read out and control structures on top of the silicon layer. Other proposals include nitrogen-vacancy centers in diamond crystals,[4] where recently single qubit operation[5] and two-qubit quantum logic gates have been demonstrated[6] along with a long coherence time[7] needed for longer computation cycles.[8]

Both proposals have in common that they need a way to align single ions in a larger array to realize a computer with several qubits. To achieve this a single ion implanter is needed, which allows to implant ions one by one into defined regions aligned to some predefined structures.

In our setup[5,9] the alignment is achieved by incorporating a scanning probe into the beamline which is used for ion implantation. The tip of the scanning probe also functions as a beam spot defining aperture by including a small hole through which the ions will be implanted into the material. Holes in scanning probe cantilevers as small as 5 nm have been achieved by focused ion beam (FIB) drilling followed by local thin film deposition to reduce the hole radius to the desired radius.[9,10]

In this article the newly designed fabrication of one of the basis components of our single ion implanter, the cantilever, will be discussed.

[a]Electronic mail: persaud@uni-kassel.de
[b]Electronic mail: ivo.rangelow@tu-ilmenau.de

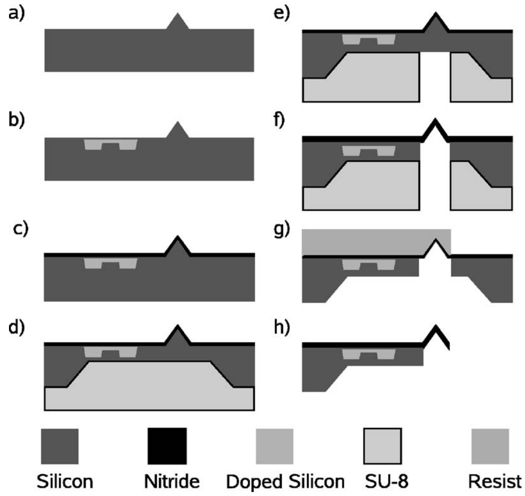

FIG. 1. Fabrication process sequences of a piezoresistive cantilever: (a) tip formation; (b) implantation for piezoresistors, heater, etc.; (c) nitride formation; (d) back etch to form the membrane and SU-8 spin on; (e) SU-8 lithography; (f) back etch to form hollow pyramid; (g) SU-8 removal and masking off of the cantilever shape; (h) releasing of the cantilever.

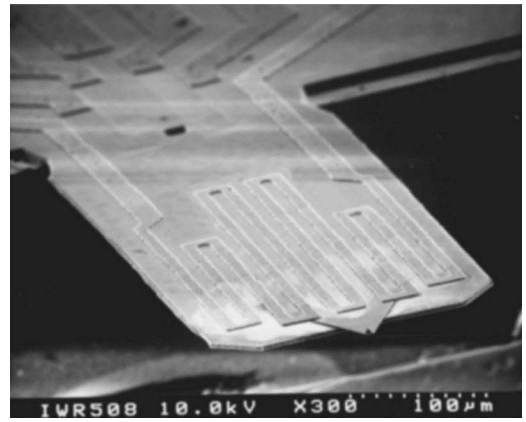

FIG. 2. Cantilever with integrated piezoresistive Wheatstone bridge, bimorph actuator, and AFM tip.

II. FABRICATION

Piezoresistive cantilevers with an integrated hollow tip were microfabricated using standard complementary metal-oxide semiconductor (CMOS) processing and double-sided micromachining techniques. The thickness of the beam of the cantilever is defined by a KOH back etch, followed by etching the back side of the pyramid to create a hollow pyramid. In the following the details of this process will be discussed (see Fig. 1).

As starting material double-side polished, 100 oriented, 10 Ω cm silicon wafers are used. The wafers are oxidized and a small area is masked off to create an atomic force microscope (AFM) tip by underetching the oxide. The so formed tip is covered with a nitride, which will form the hollow pyramid after removing the silicon tip with a back side etch in a later process step. Before the nitride layer is formed the piezoresistors are defined using standard CMOS technologies. At the same time contact pads and the resistive heater element, which will be used for actuating the beam, are also formed on the front side of the cantilever.

In order to achieve a deflection sensitivity better than $10^{-6}(dR/R)$ per nanometer the previously used piezoresistor technology has been redesigned to include especially shallow resistors. This is achieved by implanting boron for the resistors at a low energy of 20 keV and using a short rapid thermal annealing. Using shallow implantation has the advantage of placing the resistors close to the surface where the stress from bending the beam during operation is highest. Therefore a higher sensitivity of the cantilever can be achieved. Under these implant conditions the carrier transport is not affected by surface states, so that the stability of the piezoresistors is not affected.

By using a corner compensated membrane pattern and anisotropic deep etching in KOH solution at 60 °C, a silicon membrane is formed that defines the thickness of the cantilever beam. Typically the membrane is etched to a thickness of 5 μm.

To create the hollow pyramid the back side is now covered with SU-8 resist in a two step spin-on procedure to create a planar surface. With standard contact printing lithography holes are now defined in the negative resist where the pyramid should be back etched.

The pyramid is then etched using dry etching in an inductively coupled plasma (ICP) using SF_6. In the following step the SU-8 is removed by a lift-off procedure.

Now all that is left is to release the cantilever. This is done by a front side lithographic step followed by another dry etching step using ICP gas chopping with SF_6 and CH_3/Ar gases. To protect the cantilever it was masked off using a 10 μm thick photoresist AZ4562.

For actuating of the cantilever the back side can be coated with a metal to form a bilayer system.

III. OPERATION

The cantilever (see Figs. 2 and 3) can be used for contact AFM as well as tapping or noncontact operation. In contact mode the piezoresistive Wheatstone bridge is biased directly

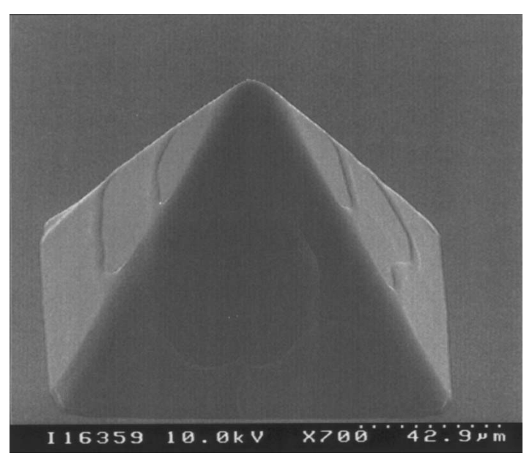

FIG. 3. Pyramid tip created on a cantilever.

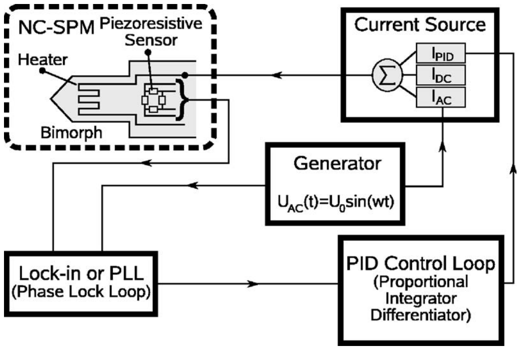

FIG. 4. Schematic diagram of the experimental setup for noncontact AFM mode.

and the output voltage of the bridge is read out and amplified to drive the feedback loop of the AFM. For noncontact or tapping mode the tip and the beam need to be oscillated. The integrated resistive heater on the front side of the beam can be used to drive the bilayer system of the beam close to its resonance frequency. By adding a dc bias to the heater voltage the cantilever can also be prebent. The dc bias also allows one to drive the heater with a current at only half the resonant frequency and still excite the cantilever at its resonant frequency. This is due to the fact that the actual heating power is proportional to the square of the driving voltage. The total driving power for our cantilevers is below 1 mW. This is enough to achieve a stable actuation. Another advantage of this method is the fact that in this setup only the beam of the cantilever is oscillated and not the whole cantilever as it is often done in other systems. This leads to less mass that needs to be moved which makes it easier to reach higher frequencies.

Figure 4 shows a typical setup for noncontact AFM using these cantilevers that utilizes the sample-tip distance dependence of the phase shift of the forced oscillation to drive the feedback loop.

Figure 5 shows a frequency response spectrum of the cantilever. Two different eigenmodes of the cantilever can be

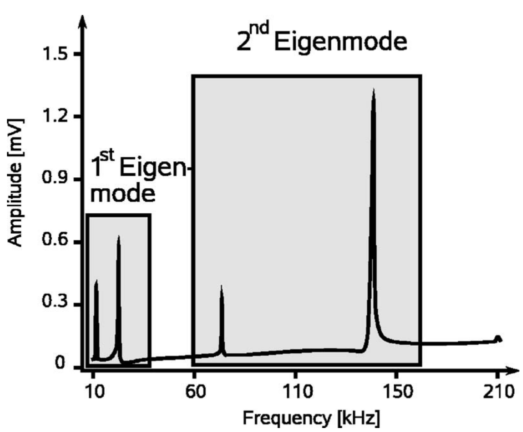

FIG. 5. Typically measured frequency spectrum by the piezoresistive deflection sensor of a thermally driven SPM probe with a bimorph actuator.

seen at 22 and 146 kHz as well as peaks at half the frequencies which is due the above mentioned effect.

IV. ION IMPLANTATION

For aligned ion implantation the piezoresistive cantilevers are combined with an ion beam. The AFM is used to image the target and place the tip so that the ions will be implanted at the right position. A small hole drilled with a FIB allows the ions to be implanted through the tip area and works as a last beam limiting aperture defining the beam spot size. By placing the hole close to the tip the distance between the aperture and the target can be minimized which will also minimize scattering effects from the ions passing through the aperture. State of the art FIBs are also able to implant ions with high lateral resolution, but the numbers of ion species are very limited and the ion energy is typically higher than 10 keV. Furthermore, alignment of the ion beam without implanting unwanted ions during the process becomes a challenge at the nanometer level. Low energy ions are desirable since the ion straggling during the implant depends on the energy of the ions. Especially for light ions an implant energy of 5 keV or below would be needed to achieve a lateral resolution in the nanometer range. Here, the technique of scanning probe microscope (SPM) tips using a nanoaperture has the advantage of being able to collimate nearly all ion species even at a kinetic energy of 1 keV or below. Assembling of nanoclusters or molecules is also a possibility. To achieve single ion implantation two different approaches are followed.

By incorporating a single ion detection the number of implanted ions can be controlled exactly. To do this either secondary electrons from the surface or electron/hole pairs created in the target material can be used. The use of highly charged ions, e.g., P^{15+} or Bi^{40+}, leads to a several orders of magnitude higher signal and therefore makes the detection of every single ion easier.[11,12] In the case of using secondary electrons for detection of the ions, the hollow pyramid also functions as a shield for electrons that are created on the back side of the cantilever, that is, inside the pyramid, since these electrons should not reach the detector. In the case of highly charged ions, the hollow pyramid does not need to shield all secondary electrons, since a decreased amount of secondary electrons from the back side will lead to a smaller signal in the detector, and therefore true signals from implanted ions can be distinguished by looking at the pulse height of the secondary electron signal. A special ion source for the production of HCI is part of the experimental setup at the E. O. Lawrence Berkeley National Laboratory.[9,13]

The second approach is to use an ion trap as a single ion source. Ion traps allow one to capture exactly one ion. By using a special designed extraction and trapping system this single ion can be implanted with very high lateral resolution. A setup using this kind of technique is in construction at Bochum and Ulm.[14]

V. OUTLOOK

The new cantilevers need to be tested now in the actual single ion implantation setup and since the current design presents the first generation of hollow pyramids as tips, we expect to be able to improve the design in future generations.

Furthermore on the processing side the yield of the SU-8 processing step needs to be optimized, since at the moment the yield of the lithography step for the back etch of the pyramid is not sufficiently high.

VI. CONCLUSION

First results of an SU-8 process are discussed for creating hollow pyramids integrated in a piezoresistive cantilever with a bilayer actuation system. The hollow pyramids enable these cantilevers to be used for single ion implantation. The technology of the piezoresistive cantilevers is well understood. The new process for integrating hollow tips in the cantilever and fabricating the cantilever in one fabrication step completely on the wafer achieved promising results, which we will optimize to reach reliable high yield production.

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