Ion Implantation with Scanning Probe Alignment

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Abstract

We describe a scanning probe instrument which integrates ion beams with the imaging and alignment function of a piezo-resistive scanning probe in high vacuum. The beam passes through several apertures and is finally collimated by a hole in the cantilever of the scanning probe. The ion beam spot size is limited by the size of the last aperture. Highly charged ions are used to show hits of single ions in resist, and we discuss the issues for implantation of single ions.

1 Introduction

There is a wide range of applications for local modification of surfaces with scanning probes[1], and deposition of metal lines through nanostencils[2, 3].

Our setup combines ion beams with scanning probes[4]. Due to the ion sources used, we can implant a wide spectrum of ions species with variable energy at precise locations into target materials. The alignment resolution is given by the integrated scanning probe and is currently of the order of 5 nm[4]. The size of the implanted area is given by the size of the last aperture, and a technique for formation of 5 nm holes in scanning probe tips has been demonstrated [5].

The advantage of this setup is that small areas can be implanted with very precise alignment and with non-invasive imaging of the area of interest. In particular for low dose or in the extreme case of single ion implantation this is a crucial requirement. This is in contrast to focused ion beam (FIB) systems, where the ion beam has to be aligned with an electron beam outside the region of interest to avoid implantation during imaging. Furthermore, low ion intensities needed for low dose implantation in a FIB require fast chopping and low beam intensities which can adversely affect beam quality and increase the difficulty of alignment imaging.

2 Experiment

2.1 Setup

Our setup utilizes two ion sources. A medium current source, which produces low energy, low charge state ions and an electron beam ion trap (EBIT). The latter produces a low emittance ($\leq 0.2\,\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$), low current beam of highly charged ions[6]. The ions are transported to a bending magnet where we can select a specific charge state. In the experiments described here, we use our medium current source to produce nA of Ar^{2+} ions with a beam energy of about 6 keV and the EBIT to produce pA of Xe^{30+} (195 keV) and Bi^{45+} (120 keV). Figure 1, shows a magnet scan of Bi^{q+} ions extracted from the EBIT. The EBIT was operated in leaky mode were ionization potential and extraction potential equaled 3.5 kV. Bismuth is supplied to the ion source from an oven. Typical ion intensities are $10^7\,{}^{\mathrm{ions}}/_{(\mathrm{mm}^2\,\mathrm{s})}$. The experimental setup is shown schematically in Figure 2.

The target is mounted on a nanometer positioning stage which has a range of 100 μm $\times$ 100 μm $\times$ 10μm. The last lens element of the beamline is positioned several mm above the target surface, and the cantilever is positioned in between. During scans the cantilever is held in a fixed position and the stage is moved to acquire the scan image. For coarse motion and alignment the cantilever itself is mounted on a flexure stage and can be positioned freely over the region of interest. The flexure stage is also used to achieve the coarse approach of the tip to the surface.

2.2 Scanning Probe

We use a piezo-resistive readout scheme to sense the deflection of the cantilever when imaging the target surface. The cantilevers have a Wheatstone bridge built in[7, 8] and a vacuum pre-amplifier ($\times 10$) integrated close to the cantilever. A second amplification stage ($\times 10 - \times 5000$) outside the vacuum is used in combination with a low pass filter before the signal is fed into the control hardware for the feedback loop.

For imaging we use tips produced by Pt deposition with a dual beam FIB[8] or glued on commercial tips. For the latter the beam of a commercially available cantilever is broken off and glued onto the piezo-resistive cantilever. An example from this technique is shown in Figure 3. Figure 4 shows an in situ image of a test sample with 50 nm wide trenches taken with the scanning. probe.

Holes are drilled into cantilevers in a FIB with a 30 keV Ga^+ beam. These micron sized holes can then be reduced in diameter by ion beam assisted deposition of platinum or SiO_2. Figure 3 shows a glued on tip with three holes of different sizes drilled into it. The insert shows a hole with a diameter of 100 nm, reduced from the initial micron size by deposition of SiO_2.

3 Results and Discussion

To test the implantation through the holes in the cantilever we use Si wafers coated with polymethyl-methacrylate (PMMA) resist and expose the resist with the ion beam. The PMMA we use has a molecular weight of 950k and the film thickness was 35 nm. After exposure the samples are developed in a 1:3 MIBK:IPA solution for one minute. Results from Ar exposure (dose $\sim 10^{13}\,\mathrm{ions/cm^2}$) are shown in Figure 5. In comparison to results reported earlier[4], we were able to improve the beam quality of our medium current ion source by additional collimation of the beam, which resulted in undistorted holes following transmission of 500 nm wide, round holes in the cantilever.

Highly charged ions are a very desirable choice for implantation of single ions, because highly charged ions not only deposit kinetic energy in the material but also large amounts of potential energy (the sum of the binding energies of the removed electrons). This extra energy results in an increased production of secondary electrons on impact[9] and also in the creation of more electron/hole pairs inside the material[10], which can make detection of low energy, single ions easier, compared to detection of single charged ions[11]. The potential energy is also independent of the kinetic energy and therefore especially shallow implants benefit from highly charged ions (HCI). In Figure 6 Bi^{45+}(E_{pot}=37 keV) were implanted into PMMA and single ion hits can be seen due to the enhanced resist development power of HCI [12]. The ions were implanted through a 2 μm wide hole in a cantilever. A single ion crater from the impact of a Bi^{45+} ion shows a diameter of 50 nm. This dopant atom is now aligned to this hole in the resist, enabling formation of a device for probing single atom effects.

Registration of single ion impacts via detection of secondary electrons requires efficient collection of secondary electrons from ion hits on the target in the electron collector, while collection of secondary electrons emitted from collimating apertures has to be suppressed. Efficient detection ($> 90\%$) of P^{13+} and Te^{33+} ions has been demonstrated without the scanning probe alignment[9], but collection efficiency for secondary electrons emitted from the surface were found to be reduced with the integration of the scanning probe. Figure 7 shows pulse height spectra of secondary electrons collected following the impact of Bi^{45+} ions on silicon targets. The mean pulse height is reduced when the scanning probe is inserted, indicating that fewer electrons reach the detector following hits on the top side of the cantilever, as compared to hits on the target. For demonstrations of single ion placement suppression of electrons from collimating apertures, and collection of electrons from true target hits have to be improved.

4 Summary and Outlook

Our setup for aligned ion implantation using a scanning probe has been presented. The resolution is limited by the hole size of the smallest aperture, currently 100 nm, and experiments with smaller holes are in progress. For small hole sizes the straggling (e.g. $\sim$ 5 nm for 50 keV Bi ions in silicon) of the ions during implantation will be of the same order of magnitude as the diameter of the hole and thus a resolution of about 5 nm for single ion placement seems possible.

Acknowledgments

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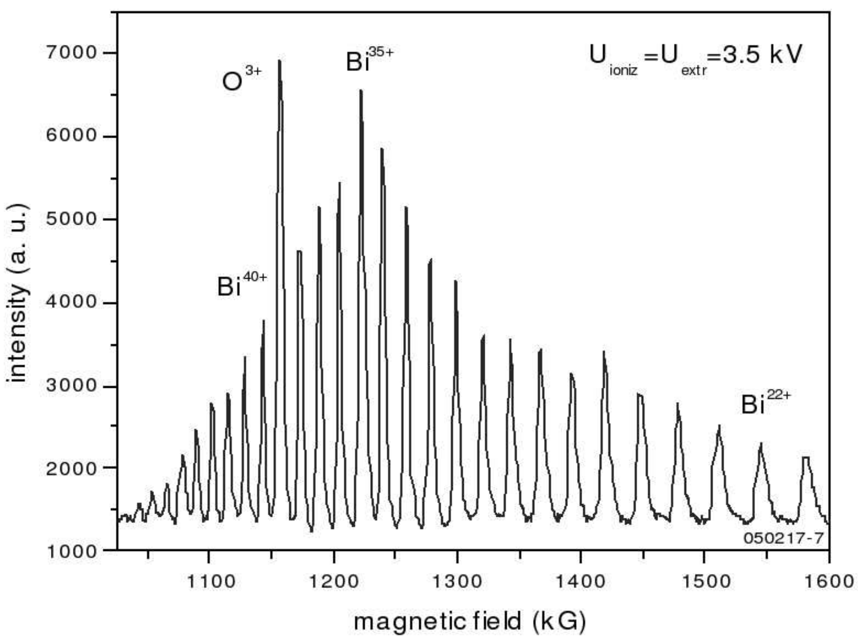
List of Figures



7000
6000
5000
4000
3000
2000
1000
intensity (a. u.)
O3+
Bi35+
Bi40+
Bi22+
Uioniz=Uextr=3.5 kV
050217-7
1100
1200
1300
1400
1500
1600
magnetic field (kG)

Figure 1

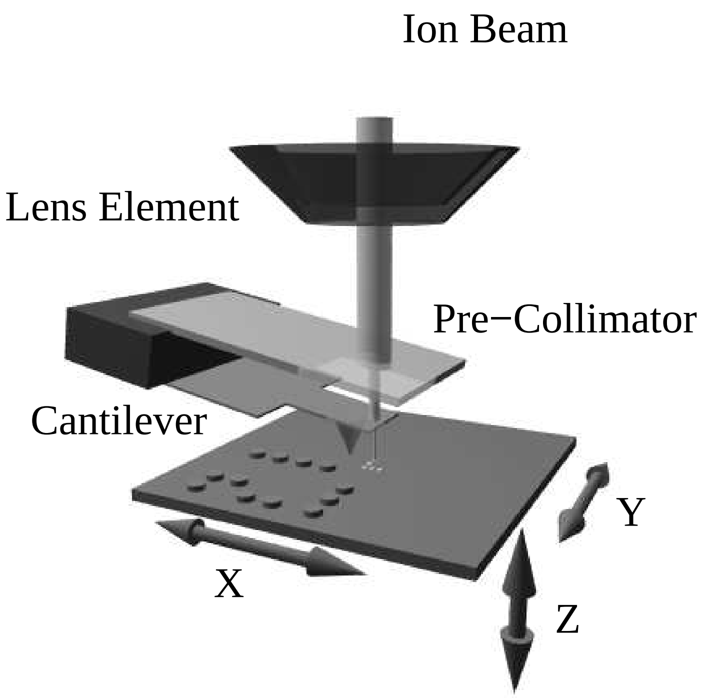
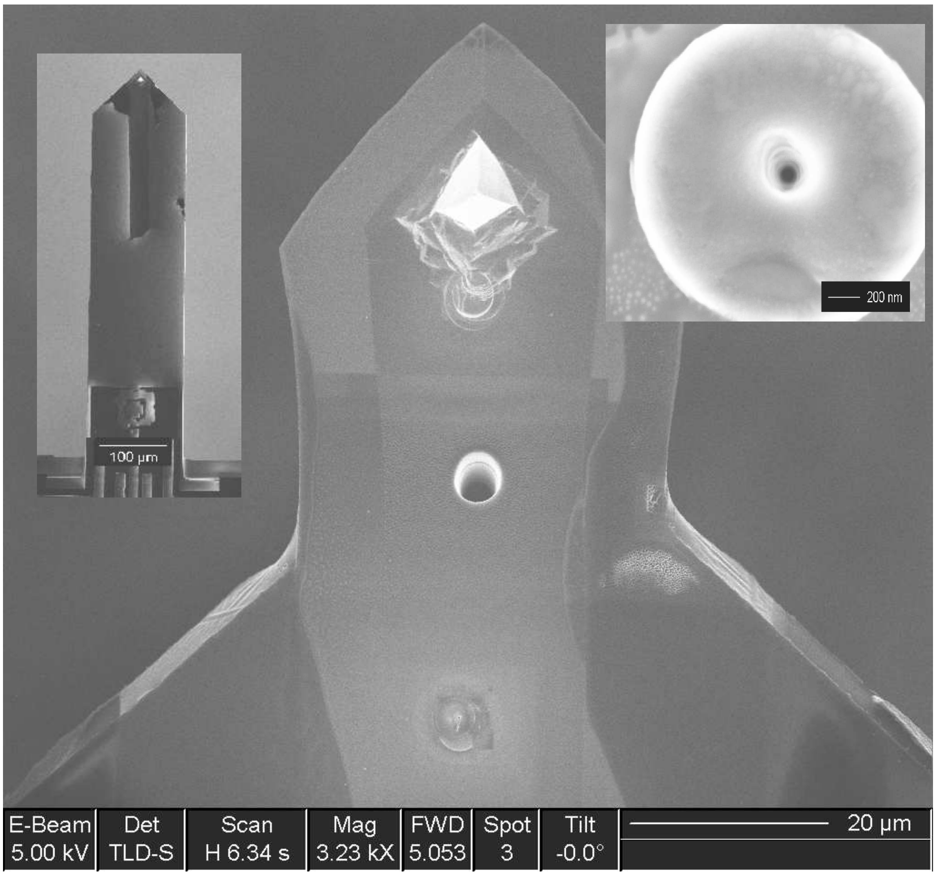


Figure 2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200 nm
E-Beam
5.00 kV
Det
TLD-S
Scan
H 6.34 s
Mag
3.23 kX
FWD
5.053
Spot
3
Tilt
-0.0°
20 µm

Figure 3

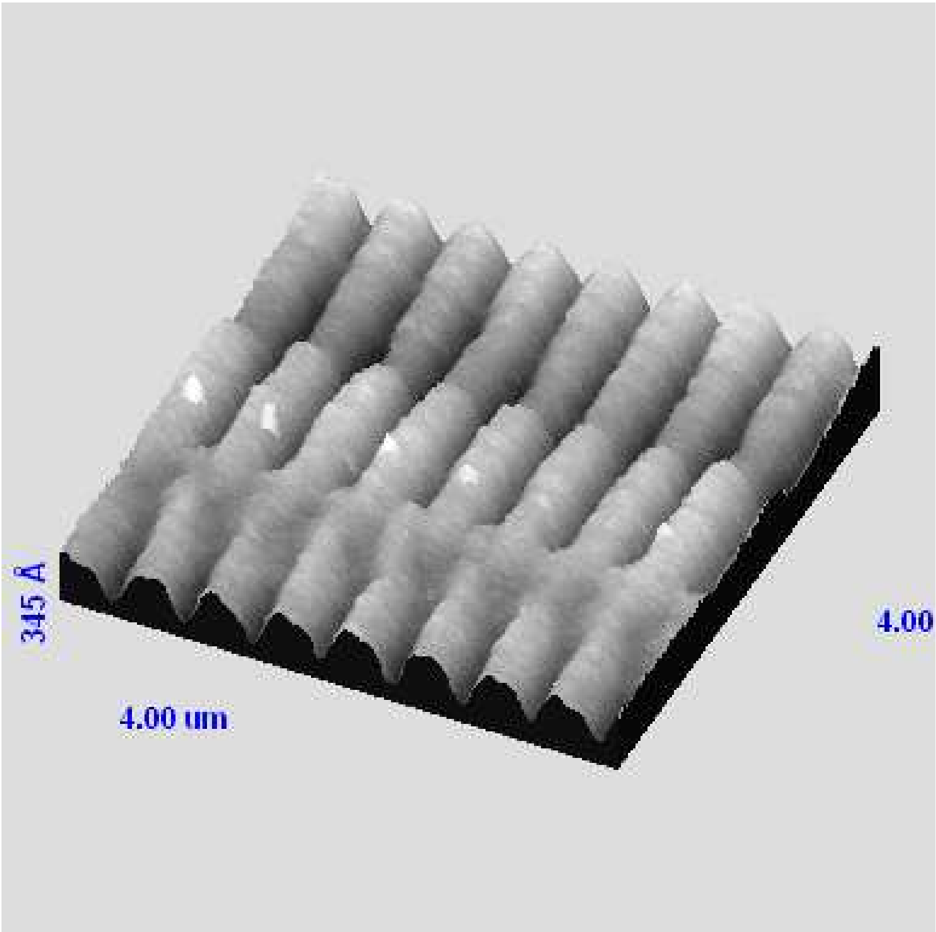

Figure 4

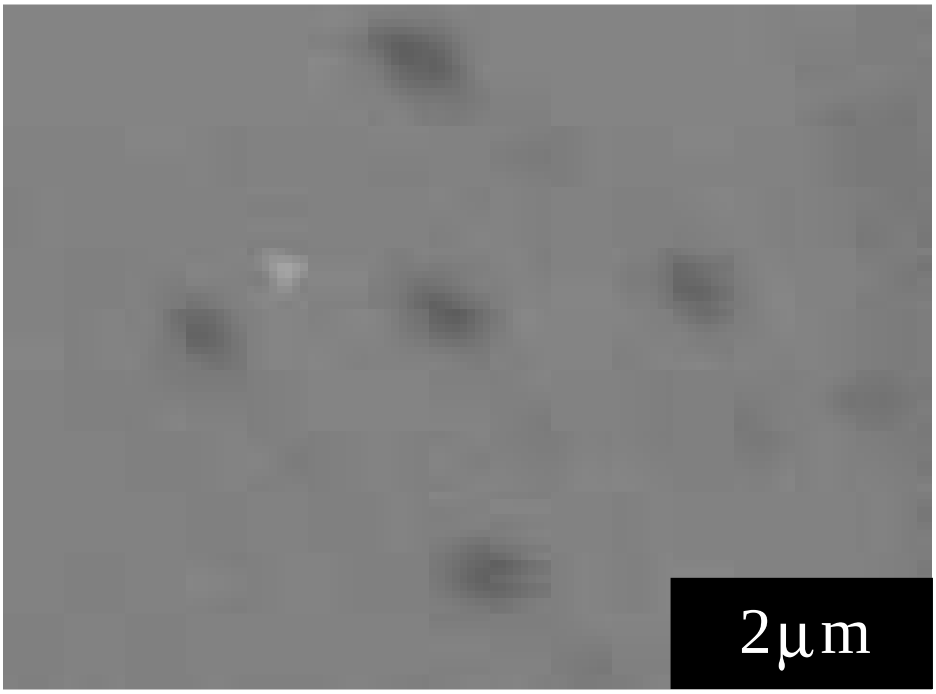

Figure 5

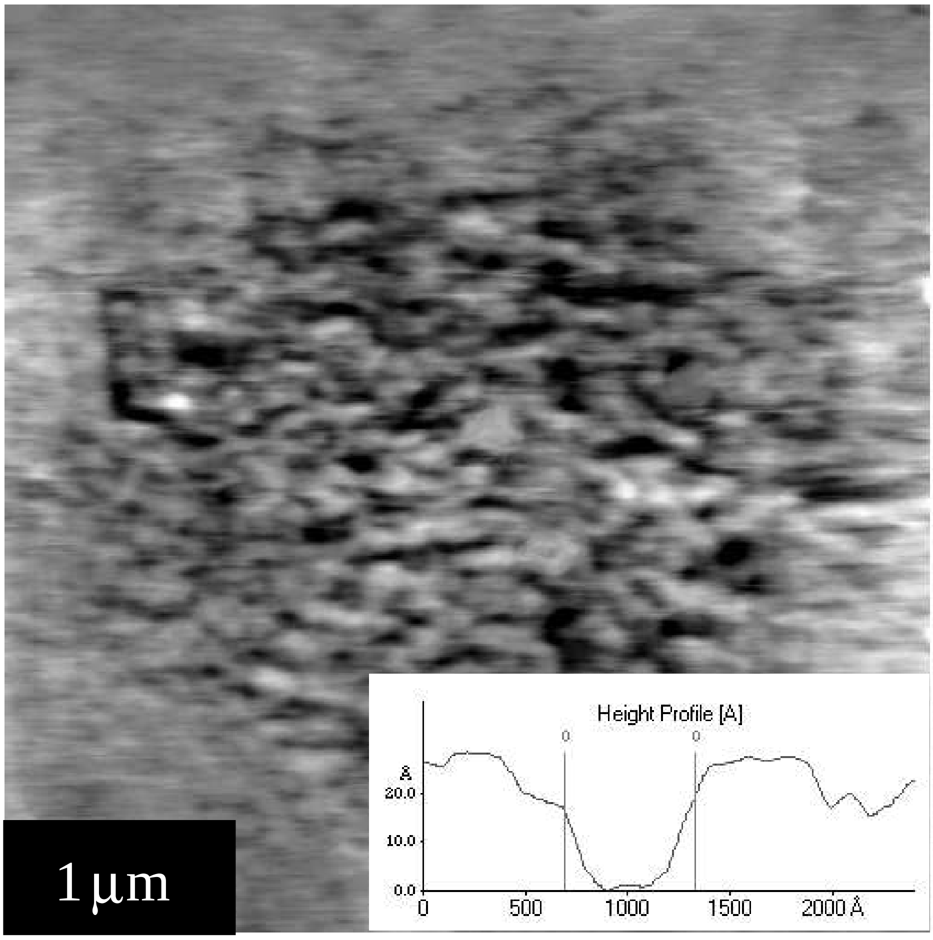

Figure 6

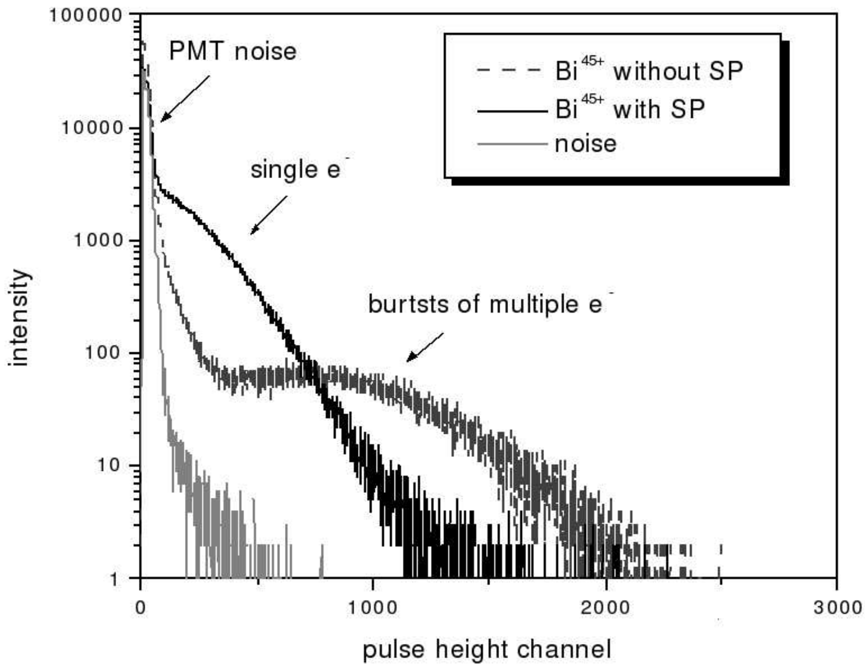
100000
10000
1000
100
10
1
intensity
0
1000
2000
3000
pulse height channel
PMT noise
single e⁻
burtsts of multiple e⁻
Bi45+ without SP
Bi45+ with SP
noise

Figure 7