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Automated wafer-scale fabrication of electron beam deposited tips for atomic force microscopes using pattern recognition

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Abstract
We present an automation technique for the growth of electron beam deposited tips on whole wafers of atomic force microscope cantilevers. This technique uses pattern recognition on scanning electron microscope images of successive magnifications to precisely place the tips on the cantilevers. We demonstrate the capabilities of the working system on a four-inch wafer of microfabricated small cantilevers with a total of approximately 2100 levers per week.

1. Introduction

Atomic force microscopes (AFMs) generate an image of sample topography by raster-scanning a cantilever with a sharp tip at the end over the sample while monitoring the cantilever deflection [1, 2].

In early AFMs, a sharp diamond fragment was glued to the cantilever to form a tip [3]. Today, commercial AFM cantilevers are micromachined using photolithography techniques [4, 5], and have integrated tips. Another kind of tip that has been used since the early days of AFMs, and is still used for some experiments today, is the electron beam deposited (EBD) tip [6–11]. EBD tips grow when an electron beam is focused onto a conductive surface inside a vacuum that has been contaminated with organic molecules [11]. EBD tips show superior properties over integrated tips, such as high aspect ratio [7, 9, 12], hydrophobic surface properties [13–15], high elastic modulus [16], low thermal mass [17], abrasion resistance, and generic tip angle [18]. The shape of EBD tips can be modified by etching with a reactive plasma [9, 12]. EBD tip composition and conductivity can be controlled by selecting suitable contaminants (precursors) [19, 20]. EBD tips provide a convenient way for tip formation on prototype or custom probes [21–23]. The reason for their rarity in experiments is the fact that, so far, they have had to be grown individually by a person operating the scanning electron microscope (SEM). The main challenges in automating this process are the proper placement of the tips on the AFM cantilever to sub-micron precision throughout a wafer, and a reliable auto-focus [24]. Here we present a system that we developed to add EBD tips to small AFM cantilevers developed in this laboratory previously by Viani [25–28], with the capability to automatically grow tips on cantilevers on a four-inch wafer, and capacity of approximately 2100 EBD tips per week. The system uses pattern recognition[3] to find the cantilevers and position the tips.

2. System architecture

2.1. Hardware

As an electron beam source, we use a Jeol JSM-5300 LV SEM with a tungsten cathode. The x and y handles on the sample stage were fitted to stepper motors, which are controlled by a two-channel stepper indexer with an RS-232 interface. For SEM control, the beam position, zoom, coarse and fine focus and intensity signals were tapped inside the SEM (figure 1), and connected to a National Instruments DAQ board (figure 1).

[3] National Instruments. IMAQ Vision. In.

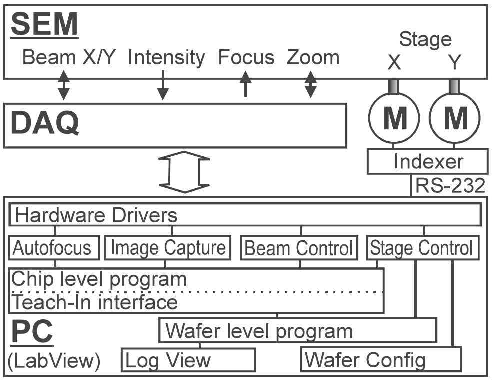

Figure 1. Simplified diagram of the system.

2.2. *Software*

The software was written in LabView, and consists of 80 sub-VIs (sub-programs), each of which belongs to one of several function groups (figure 1). A layer of hardware driver VIs provides robust communication and unit conversion/calibration. The image capture functional group extracts the current SEM image from the sampled beam x/y and intensity signals, compensates for image centre offsets, and provides scale information for these images.

The chip level program group implements all process steps for the treatment of one chip on the wafer. It calls several basic functions that control the SEM, such as zoom, auto-focus, move stage, match pattern, and grow tip. For a new type of cantilever chip, these commands are evoked manually to find the cantilevers on the chip, focus on them and grow tips. During this teach-in step, all commands are saved in the form of a macro language for later automated execution on all other chips. This macro language also provides for branching, sub-program calls, error handling, and logging.

The wafer level program group is an environment that edits and later recalls the coarse layout of the wafer, that is, the position of all cantilever chips, and their respective chip type. During execution, the wafer level program moves the SEM stage to the position of a chip, then calls the chip level program group with the proper chip type as a parameter. On return, it colour codes the chip on the screen, green for success, red for errors. The operator can select any group of chips and start the program, then watch the progress on the wafer as the chip symbols change colour. This view can also be remotely monitored over the internet. After execution, the chip symbols can be selected to display their log-files and logged images for quality control and debugging.

To find the cantilevers on a chip, the system identifies features in the SEM image using pattern recognition. After a structure is recognized, all following moves are referenced to that structure. After multiple iterations of recognizing features and then zooming in, the cantilever is found and centred. The pattern recognition used is IMAQ Vision, a commercial add-on package for LabView. For the production of sharp EBD tips, it is critical to optimally focus the electron beam on the target surface. The auto-focus routine is invoked before growing each tip. It consists of a coarse focus step that controls the coarse focus buttons on the SEM, and a fine focus step that controls the SEM's fine focus voltage. To evaluate the current focus, a slow single line scan is performed over the edge of the cantilever. The resulting function consists of a high plateau in the cantilever region, a downward slope in the edge region, and a low plateau off the cantilever. This function is then fitted, and the parameter for the steepness of the downward slope represents the sharpness of the edge and, hence, the focus quality. Sweeping the SEM's focus controls, this parameter can be maximized to auto-focus the electron beam.

The alternative approach of taking the derivative of the line scan, which in the edge region represents the beam profile, and minimizing the deviation of a Gaussian fit turned out to be less robust in the fit step.

Because the system works without supervision on precious full wafers, robustness was an important design parameter. The system has to recognize and handle errors in the process in a non-destructive way, automatically recover if possible, and document success and failure in a way recognizable by the user. Errors in the process are recognized when the system fails to find features that should be there, or fails to auto-focus. When this happens, the system recovers at the earliest process step that does not depend on the failing step. Progress of execution and log-entries are routinely backed up on hard drive to minimize yield losses due to possible computer crashes and power failures.

3. System test

After a series of smaller test runs, a four-inch wafer of approximately 300 small silicon nitride cantilever chips with seven cantilevers per chip was prepared for EBD tip growth. 200 Å of Cr–Au were thermally evaporated onto the cantilevers to provide conductivity and enhance the reflectivity of the AFM cantilevers. Next, the wafer was dipped into dilute paraffin oil solution to create a thin film of paraffin oil on the wafer surface. This film provides the organic that is later polymerized into EBD tips by the electron beam.

Then, the wafer was mounted inside a specially designed frame that attaches to the SEM stage. The frame provides good grounding of the gold coating on the wafer through a Be–Cu spring washer.

After insertion into the SEM, the coarse position and alignment of the wafer inside the chamber were manually referenced by two reference points on the wafer. The coarse position of all chips on the wafer was then programmed. Next, a chip-level program was written using the teach-in environment: first, an image of the whole chip at low magnification is trained into the system, then a relative move and zoom step centre the cantilever array in the view-field. The next reference image is of the cantilever array. From there, relative moves to the individual cantilevers, followed by another zoom step, bring single cantilevers into the view-field. At each cantilever, the program calls the same sub-program that recognizes and centres the cantilever (figure 2), then calls the auto-focus command, then positions the beam at the designated point for EBD tip growth and turns off the SEM's beam scanning unit. After a defined dwell-time, the SEM takes an image for the log-file, and the sub-program returns for execution of the next cantilever.

Once this sequence has been programmed, the wafer-level program moves the stage to each chip, then calls the chip-level

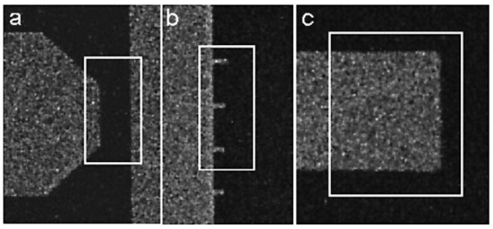

Figure 2. The steps of zooming into a cantilever. The framed area has been matched to a reference image by the pattern recognition. (a) Top view of the front part of a cantilever chip, 50× magnification. (b) Front edge with cantilever array, 500× (c) single cantilever, 10 000×.

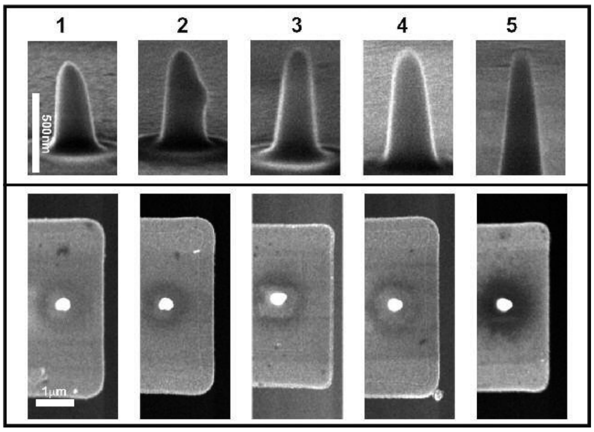

Figure 3. SEM micrographs of five finished EBD tips, in side view and top view. The tips were selected randomly from locations across the wafer.

program to execute the sequence on that chip. A series of all logged images for each chip can later be viewed from the wafer-level program.

4. Results

The wafer described above was fully processed within a week. In this time, approximately 2100 EBD-tips with tip radii of 56 ± 7 nm and a length of 818 ± 261 nm (figure 3) were grown on the cantilevers. We ascribe the relatively large tip radius to the limited resolution of our SEM. Others [11, 18] routinely achieve tip radii of 3 nm after sharpening [18]. The variation in tip length of 28% is also relatively large; however, the variation in the length of tips grown consecutively on a given chip is only 3.4 ± 1.9%. This indicates a change in tip length over extended periods of time, which could be caused by filament deterioration, or other factors.

The system recognized and marked all locations with defective or missing chips or cantilevers, and showed a rate of failure to grow tips on existing cantilevers of approximately 0.2%.

The average positioning error of the tip on the cantilever was measured from the seven tips of five cantilevers randomly picked from across the wafer, and determined to be 154 nm (figure 4).

The only required user interventions were an exchange of the SEM cathode after about 100 h, and a daily readjustment of the cathode current. The cathode current was adjusted to

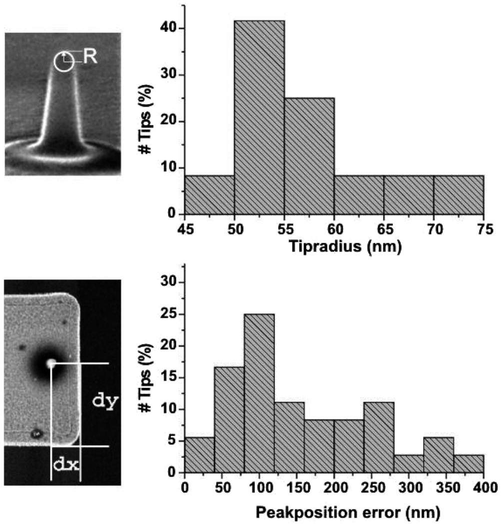

Figure 4. Distribution of tip radii and positioning errors on cantilevers.

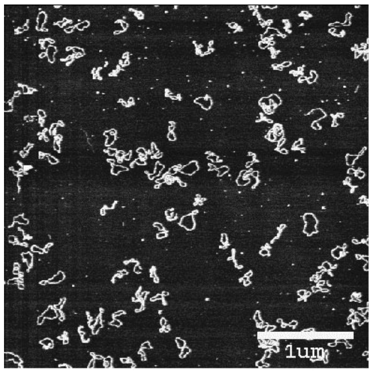

Figure 5. AFM image of DNA on mica, scanned in liquid in 25 s using a small (width = 5 μm) SiN prototype cantilever with automatically grown EBD tip. DNA line width approximately 20 nm.

just below the second peak in the SEM's imaging intensity in compliance with the SEM manual, and slight changes from this position could be observed on the timescale of a day. Though these adjustments were not very time consuming, they could certainly also be automated by giving the computer control over the cathode current. Other cathode types with a longer lifetime could also render user interventions unnecessary.

We found that when using paraffin oil coated wafers, venting the SEM with dry gas is critical, because condensation destroys the oil film, and we were not able to strip and re-coat the wafer with sufficient uniformity.

To consider the economy of automating EBD tip growth, assume the total cost of a trained technician to be \$60 h^{-1}. At a rate of 12 tips h^{-1}, the technician cost saved by automation is \$5 per EBD tip.

EBD tips automatically grown on small cantilevers with this system are now in routine use in our AFM experiments [29, 30]. Figure 5 shows an image of DNA on mica [31, 32] acquired with a small cantilever, and one of these tips in only 25 s. The measured line width of the DNA is approximately 20 nm, a typical value for AFM imaging of DNA.

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