Non-Contact Atomic Force Microscopy Fabrication of Gold Nanowire Electrodes

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Atomic force microscopy (AFM) is currently one of the simplest, fastest, and most precise processes by which one can fabricate surface nanostructures. One of the advantages of AFM is that even operated in ambient conditions it can reliably realize nanometer-scale designs. This avoids the time and complication involved in executing experiments in ultra-high vacuum. To ensure that the operation still maintains a high level of precision, frequency-modulated non-contact AFM mode is used. This operation mode provides maximum tip-sample force-distance control. Previous research by other groups has shown that by operating AFM in this mode it is possible to fabricate gold nanowires that are consistently ~40 nm in diameter [1]. Our present work is in improving the precision of these results, in order to create sub-10 nm wires. To achieve smaller wire diameter, we will perform the wire deposition process using a specialized cantilever, fabricated by attaching a thin gold wire at the end of a commercial cantilever and sharpening the wire apex by focused ion beam [2]. Wires of such a scale should be capable of serving as electrodes for single-molecule conductance analysis, perhaps for molecules as small as pentacene. Such conductance measurements would open the door to the incorporation of smaller molecules in design of innovative circuit components.

[1] M. E. Pumarol, Y. Miyahara, R. Gagnon, and P. Grutter, Nanotechnology **16,** 1083–1088 (2005).
[2] Kotone Akiyama, T. Eguchi, T. An, Y. Fujikawa, Y. Yamada-Takamura, T. Sakurai, and Y. Hasegawa, Review of Scientific Instruments **76**, 033705 (2005).

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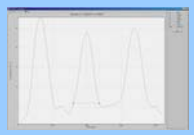
Problem Statement & Goals

Problem Statement

Image from: http://en.wikipedia.org/wiki/Image:Pentacene.png

Creation of sub-10 nm electrodes is crucial for conductance measurements of small molecules, such as pentacene. This conductance analysis is impossible with larger-scale electrodes, since many small molecules can simultaneously bridge a larger electrode gap. The result is collection of bulk data, which has been shown to be the theoretical equivalent of having nothing between the electrodes at all [1].

Goals

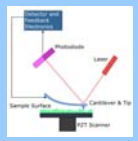


- Replication of results published by another group in 2005: consistent production of ~40nm wide gold nanowires, up to 55μm in length [2]
- Minimization of wire size by:
  - -improvement of FM-AFM techniques
  - -use of a unique cantilever with a sharp gold tip [3]

AFM Background

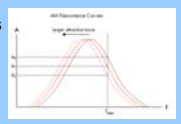
Basic Characterization

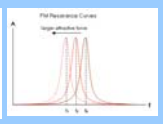
Image from: http://en.wikipedia.org/wiki/Image:Atomic_force_microscope_block_diagram.png



- Scanning probe microscope capable of atomic resolution
- Change in cantilever oscillation, due to tip-sample interaction, results in a topographical surface map
- Advantages over other microscopes:
  - unlike electron microscopes, can image samples in air and under liquids
  - unlike STM, can image non-conductive samples
- Mode of operation depends on quality factor, $Q = f_0 / \Gamma$, where f_0 = resonance frequency and Γ = bandwidth of resonance curve

Operating Modes



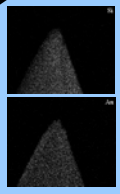


Both modes maintain tip-sample force (F, and hence tip-sample distance, z) and cantilever oscillation amplitude (A) and frequency (f) constant, but do so by different means.

Mode	Amplitude modulation (AM)	Frequency modulation (FM)
Because the AFM is operated in _____, quality factor (Q) is _____, making it easier to detect change in_____ when resonance curve shifts in response to F change. Therefore, feedback maintains F constant (by adjusting z) based on the calculation _____.	Air Low Amplitude $F = \lvert A_0 - A_1 \rvert$	Vacuum High Frequency $F = \lvert f_0 - f_1 \rvert$

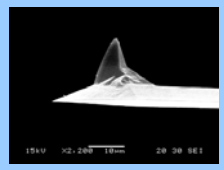
Lithography Methods

Tip Preparation



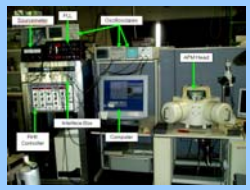
SEM-EDS images showing Si and Au content areas on in tip; complete overlap indicates complete coating

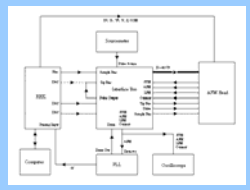
Deposit 100nm thick gold coating on tip of conventional Si cantilever ($f_0 \approx 250$ kHz) using an ion coater.

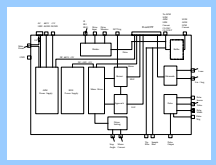


SEM image of gold-coated tip

AFM System Configuration





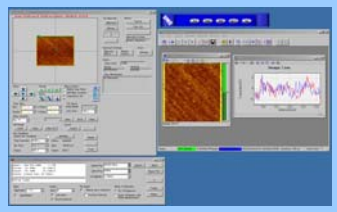


- Interface box connects AFM head (Shimadzu SPM-9600) to SPM controller (RHK SPM-100)
- Parameter adjustment by:
  - phase-locked loop (PLL) controller (nanoSurf)
  - XPMPro, software for the SPM controller

Operation Conditions

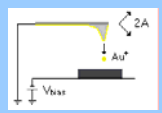
- FM mode—provides most precise tip-sample force-distance control
- Room-temperature and medium vacuum (3 Pa, necessary for maintaining high $Q \approx 20{,}000$)—minimizes setup time and complexity compared to conventional ultra-high vacuum (UHV) FM-AFM systems

Imaging



- Search for a clean, flat surface
- Calculate nm-to-amplitude-setpoint relation by comparing the z of images taken at two different setpoints

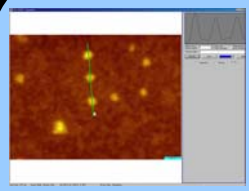
Gold Deposition



- Re-adjust setpoints for cantilever oscillation amplitude and tip-sample distance
- Turn off tip-sample distance feedback
- Pulse sample with a negative bias to deposit Au dot
- Turn feedback on again, retract and move tip to next deposition location, then turn feedback off again
- To create a wire, apply repeated pulses such that dots overlap

Results

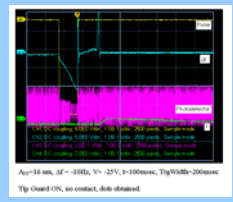
So Far



- Successfully deposited dots of diameter ~40nm
- Begun pulse parameter manipulation, examining effects on:
  - Various AFM signals (Δf, photodetector, z)
  - Success/failure of dot deposition
  - Size of dots deposited

Next Steps

- Pulse optimization by parameter adjustment
  - A_{opp} = operating amplitude
  - Δf = tip-sample force setpoint
  - V = pulse voltage strength
  - t = pulse duration
  - D = dissipation (always set to minimum)

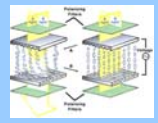


Tip Guard ON, no contact, dots obtained.

- Interfacing with LithoEdit programs to speed and abstract the drawing procedure—sample LithoEdit program for drawing a dot at position (15, 10)

Conclusions

A FM-AFM system provides greater force-distance control than an AM system, but FM-AFM is a newer field whose capabilities outside of UHV conditions have not been extensively investigated. This work is concerned with developing a FM-AFM system for use in less controlled atmospheric conditions, which may yield a valuable tool for many applications beyond lithography.



LCD mechanism

Image from: http://www.sanoma.com/newsletter/Oct04/LCDTechnology/1_files/image007.jpg

Within the scope of this particular experiment, FM-AFM improvement coupled with use of a unique, sharp gold tip could provide a precise enough system for sub-10 nm wire fabrication.

Possible application of these wires: conductance measurements for molecules such as pentacene, a promising material for use in organic thin-film transistors (TFTs) of liquid crystal displays (LCDs).

TFT

Image from: http://www.mitsui-chem.co.jp/techno/images/tab_04_img_04.jpg

Sources

[1] Dadosh T, Gordin Y, Ktahne R, Khivrich I, Mahalu D, Frydman V, Sperling J, Yacoby A, and Bar-Joseph I, Nature **436,** 667 (2005).
[2] M. E. Pumarol, Y. Miyahara, R. Gagnon, and P. Grutter, Nanotechnology **16,** 1083-1088 (2005).
[3] Kotone Akiyama, T. Eguchi, T. An, Y. Fujikawa, Y. Yamada-Takamura, T. Sakurai, and Y. Hasegawa, Review of Scientific Instruments **76,** 033705 (2005).