Atomic Force Microscope Deposition Assisted by Electric Field

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Abstract. This paper introduces atomic force microscope (AFM) deposition method to fabricate nanostructures and nanodevices. Field emission theory is introduced in this paper, which provides theoretical explanation for AFM deposition. Dot matrixes are fabricated by AFM deposition on three different substrates, Si, Au and GaAs. Differences of deposition on the three substrates are discussed. AFM deposition has many practical applications. For example, AFM deposition can be used to solder nano components together to improve electrical properties of nanodevices. Besides nanosoldering, AFM deposition can also be used in fabrication of nanodevices. Thus AFM deposition is a valuable research field for future massive applications of nanodevices.

Introduction

AFM deposition method is an important method for nanofabrication [1, 2, 3]. It has potentials to improve electrical properties of nanodevices by soldering nano components together [4, 5]. Also it has potentials to be used for fabrications of metal–oxide-semiconductors by depositing metal to an insulating substrate [6]. AFM deposition requires conductive probe, because AFM deposition is realized under the assistance of electric field [1]. Usually metal coated AFM probes are used in deposition. Fig. 1 shows the schematic diagram of AFM deposition. A voltage is applied to the AFM probe and the substrate. A very strong electric field can be aroused because the tip of the AFM probe is very close to the substrate[7]. According to field emission theory [8, 9, 10, 11, 12], the atoms on the tip will be ionized and powered by the electric field. If the electric field reaches the threshold, atoms on the tip will be emitted toward the substrate. The emitted atoms accumulate on the substrate and form a metal island. The threshold electric field depends on the materials of the substrate and the tip. Tsong et al figured out that the threshold electric field should be 6V/nm when the tip was gold coated and substrate was gold [9]. As for insulating substrate, a higher electric field threshold is needed [13]. Koyanagi et al figured out the threshold was 13V/nm on silicon, which was covered by a thin silica film [6]. Under instructions of field emission theroy, we carried out experiments of deposition on three different substrates, including Si, GaAs and Au. Then we discuss the experimental results on the three substrate.
Electric field simulation

According to Tsong and Koyanagi, electric field needs to reach a threshold before deposition can be realized. However electric field is hard to be controlled directly. Actually what we control in experiments is voltage. An important question is how much is the electric field after a voltage is applied to the AFM probe. Thus we simulate the electric field using finite elements method (FEM). According to Poisson’s equation, electric field can be calculated by differential Eq. 1:

\[-\nabla \cdot \left[ (\varepsilon / T + \sigma) \nabla V - \left( J' + P / T \right) \right] = \rho / T.\]

Among Eq. 1, \(\nabla\) is Hamiltonian operator, \(\varepsilon\) is dielectric constant, \(\sigma\) is conductivity, \(J'\) is external current density, \(\rho\) is space charge density, \(P\) is polarization vector, and \(T\) is time step. According to Eq. 1, electric field simulating result is shown in Fig. 2(a). Then we list out peak electric fields of multiple simulations under different voltage and different tip-substrate separation. These peak electric fields form a cluster of curves as shown in Fig. 2(b). From Fig. 2(b) we can know how much voltage should be applied to arouse deposition when tip-substrate separation is set a constant, or how much is the tip-substrate separation when applied voltage is set a constant.

Fig. 2 (a) Electric field simulation results when tip-substrate separation is 5nm and applied voltage is 20V. (b) Peak value of electric field under different voltages and different tip-substrate separations. These curves can give instructions about how to set up deposition parameters.
Experimental preparations

Our AFM is a Bruker product, Dimension 3100. It uses laser to detect deformation of AFM probe cantilever. Our AFM probe is coated with 20nm-thick Cr first, and then 20nm-thick Au. The radius of tip curvature is less than 50nm. As for substrates, we chose Si (110), GaAs and Au. Among them, Au is conductive substrate, and GaAs is a semiconductor substrate. Si (110) is also a semiconductor material. However our Si is covered by about 1.5nm-thick film of silica, so actually the Si substrate is an insulating substrate. All our experiments were carried out in air. The ambient temperature was set at 20 degree, and the ambient humidity was set as 50%. The voltage was supplied by a digital source meter, which can provide voltage from 5µV to 1100V. The substrates were cleaned by ultrasonic machine in deionized water for 3 minutes, and then dried with nitrogen. Before deposition, first the substrate is scanned to get a frame of picture of the substrate surface. Then choose a flat zone, where depositions are going to happen. After that the AFM probe tip is located to the depositing position. A very important step is to control the distance between the probe tip and the substrate. If the tip-substrate distance is too big, deposition may fail because voltage amplitude is limited under 30V for the safety of the AFM. After all the preparations well done, deposition can be aroused by applying a voltage. In our experiments, duration of the voltage is set as 10ms.

Experiments and discussions

Deposition on Si substrate. Fig. 3(a) shows the deposition pattern on Silicon substrate. All the 21 dots were fabricated under 30V voltage. Typically the width of the dots is about 150nm. Actually AFM is not totally accurate when measuring width because of broadening effect. Most of the dots have heights between 2nm to 3nm, except one outlier is extraordinarily as high as 5.442nm. The mean value of the heights is 2.502nm, and the variance is 0.5448nm$^2$. Without considering the outlier, the mean value and the variance of the heights of the other 20 dots will be 2.3539nm and 0.0955nm$^2$ respectively. Obvious the variance reduced dramatically without considering the outlier. Fig. 3(b) lists out the heights of the 21 dots.

![Deposition on Si substrate](image)

Deposition on GaAs substrate. Besides Si substrate, we deposited a 4 by 5 dot matrix on GaAs substrate. All the fabrication parameters were kept the same with deposition on the Si substrate. As Fig.4(a) shows, the deposition repeatability is not as good as deposition on Si substrate. The typical width of the dots in Fig.4 (a) is 500nm. The heights of dot 1 to 20 are listed out in Fig.4(b). The mean height is 7.032nm. The variance of the heights is 7.1748nm$^2$. That means the error of heights in Fig.4(b) can be up to 38.1%, while the error of the dots on Si substrate is only 29.61%.
Deposition on Au substrate. Au is a conductive substrate. In order to facilitate comparison, we used the same parameters to deposit on Au substrate. Fig. 5(a) shows the deposited dots on Au substrate. The repeatability on Au substrate is the worst one among the three substrates. Dot 20 in Fig. 5(a) has a width only about 100nm, while dot 1 is as wide as 300nm. The heights of dots in Fig. 5(a) also vary dramatically. As shown in Fig. 5(b), dot 14 is as high as 62.157nm while dot 20 is only 8.066nm high. Specifically, the mean height of dots in Fig. 5(a) is 28.2116nm, and the variance is 209.0846nm$^2$, so the error of heights in Fig. 5(b) is as large as 51.25%. Thus we fabricated highest dots on Au substrate, but repeatability of deposited dots in Au substrate is the worst among the three substrates used in our experiments.

Summary

Three dot matrixes were deposited on Si, GaAs and Au respectively. All the three experiments were carried out under the same parameter, but the depositing results are not similar. On Si substrate we realized best accuracy among the three experiments, but the heights of the dots are lowest. Because the Si substrate is covered by a thin silica film, the Si substrate is actually an insulator substrate. Dots deposited on GaAs substrate have medium heights and medium accuracy. At last, 25 dots were deposited on Au substrate, which have the biggest heights but worst accuracy. Our three substrates are insulator substrate, semiconductor substrate and conductor substrate respectively. From these three experiments, we can conclude that deposition on insulator substrate is harder to carry out. This meets
the conclusion of reference [3]. Our explanation for this is the insulator film covered on Si increases
the barrier from the AFM probe tip to the Si surface. Thus more power is needed for atom on the tip to
be emitted to the Si surface. As for the accuracy variation of the three dot matrixes, we believe it is
caused by morphology change of the probe tip. After every deposition, the probe tip will lose material
and have a different morphology. When depositing on Si substrate, only small quantity of material
leave the tip, so the tip morphology keep similar during the whole experiment. Consequently, high
accuracy is derived. While depositing on Au substrate, every deposition will cause a severely change
of the tip morphology, so the heights of the deposited dots on Au substrate become more
unpredictable.

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