

Chromium Nanodot-array Deposition using Atomic Force Microscopy

Abstract—Chromium nanodot deposition by atomic force microscopy (AFM) is demonstrated for the first time. An oscillating Cr-coated AFM cantilever is brought close to the substrate surface by the engage process in a wavemode operation and a negative tip voltage is applied to form a strong electrical field to transport the Cr atoms from the tip to the surface. An array of nine Cr nanodots around 90nm in diameter and 0.3nm to 0.5nm in height is fabricated by changing the tip positions at room temperature and in ambient conditions. It is found that the deposition is an intermittent contact process, which is avoided by most researchers for other metal nanoscale dot depositions, such as gold. A deposition mechanism is proposed, with supporting results from further experiments. Our research shows that it is possible to obtain much smaller features for application of nanoelectronics with this method by controlling the deposition time and the applied voltage.

Keywords- Cr nanodot; AFM; deposition; array

I. INTRODUCTION

A major challenge in research on nanoelectronic devices is to create desirable nanostructures such as nanodots, nanowires etc. Scanning probe microscopy (SPM) or AFM-based surface modification techniques makes it possible to directly modify the surface and deposit metals by applying a voltage (pulse) between the tip and the sample. Several research groups successfully fabricated gold nanodots or nanowires on various substrates by using either SPM or AFM [1,2,3]. Their deposited nanodots are typically in the tens of nanometers range. For application of nanoelectronic devices such as single electron transistors (SET), however, the dimensions are still too large to let the devices work at room temperature according to relation of energy and nanodots dimension [4]. Since gold atom clusters have large surface tension they tend to move along the surface to form large dots at stable sites such as surface defect areas. This makes it hard to fabricate smaller size dots or to control the dimensions in the desired range. On the other hand, Cr is known as a good adhesion promoter for noble metals on substrates such as glass, and has advantages over gold [5]. If Cr clusters (say a few dozen of Cr atoms per cluster) can be deposited as seeds for nanodot formation of a noble metal, we can use it to pattern a surface and then carefully evaporate a noble metal to form nanostructures for devices. This may make SETs possible to work at room temperature or even higher. In this paper, we present our results on this research to prove that it is possible to deposit Cr nanoscale dots by AFM.

II. EXPERIMENT

The deposition experiments are performed with a Quesant Q-250 AFM operated in wavemode (tapping mode) at room temperature in ambient conditions. We modified the system to allow a negative voltage from the voltage source to be able to connect to the tip. The oscillating frequency is set by the equipment itself with auto engage step; normally it is about 160 kHz. The oscillation amplitude is set at 140nm. After engage, the distance between the tip and the surface is in the range of a few nanometers ($\ll 10$ nm) according to the factory specification. The cantilever and tip is made from silicon (radius of curvature < 35 nm, 15 – 20 μ m in height, full tip cone angle < 20 degree, force constant between 25 to 60N/m) and coated with Cr (thickness = 20nm).

To obtain a fairly flat surface, we cleave a (100) N-type GaSb wafer along [110], and then mount it on a piece of tin-coated copper foil using conductive adhesive (silver paste). The wire soldered with the copper foil at one end will be connected to the voltage source ground to form a closed circuit with the tip. The schematic is shown in Fig 1.

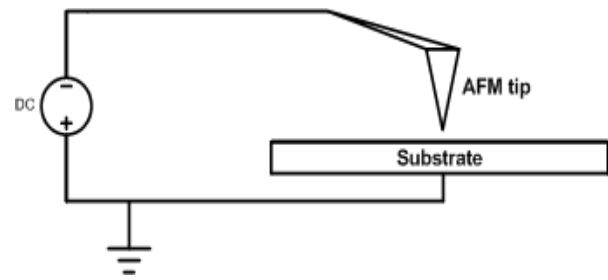


Fig 1 Experimental set-up

In order to deposit a dot, a negative voltage is applied between the tip and the sample by manually turning on the switch; otherwise, the circuit is left open. In this experiment, the voltage is set at -32v DC and the deposition period of each dot is 30 seconds.

Before deposition, the surface is scanned with the Cr-coated tip to localize a desirable area, and the image is taken for comparison with that obtained after deposition to avoid any confusion.

III. RESULTS AND DISCUSSION

1. Cr nanodot array

With the system settings and operation above, a nine-dot array of Cr is created for the first time by changing the coordinates of the tip. The AFM image is shown in Fig 2. We start from the center position and then change the coordinates of the tip along X or Y by 800nm. The pitch in Fig 2 is about 820nm, which is very close to the value that we set. The dot size is around 90nm in diameter and 0.3nm to 0.5nm in height as illustrated in Fig 3. They are fairly uniform and reproducible. It should be mentioned that we could reduce the size of deposited dots and the space between each dot, but it is very hard to find them during the following image scanning due to the limitation of flatness of the substrate. Furthermore, the Cr-coated tip is relatively large and the resolution of the image is also degraded.

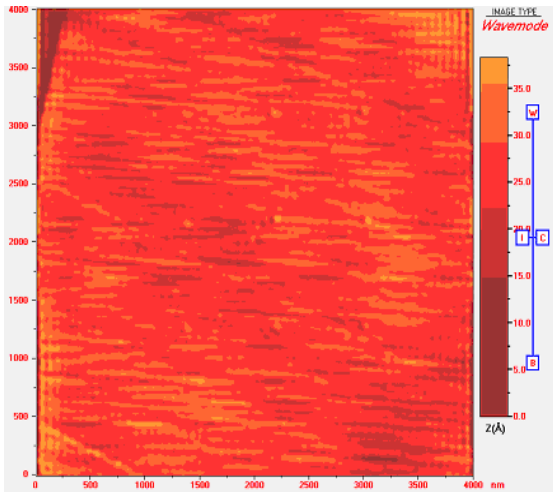


Fig 2 AFM image of Cr dot array on GaSb substrate by applying -32V DC to the tip

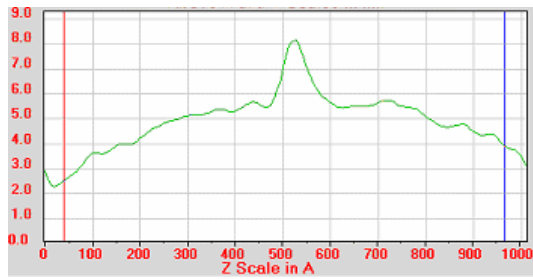


Fig 3 Typical dimensions of the nanodots

2. Nanohole array

The Cr on the tip is initially about 20nm thick, but after many runs of deposition, it is almost used up. In this situation, holes and dots appear in the same process. When the Cr is completely gone from the tip, only holes can be produced on the substrate. Fig 4 and Fig 5 illustrate an image of nine-hole array and dimensions of the holes respectively. We think the formation of the holes is a thermal process due to direct

contact. This will be discussed more in detail in the following section to explain the deposition mechanism we propose.

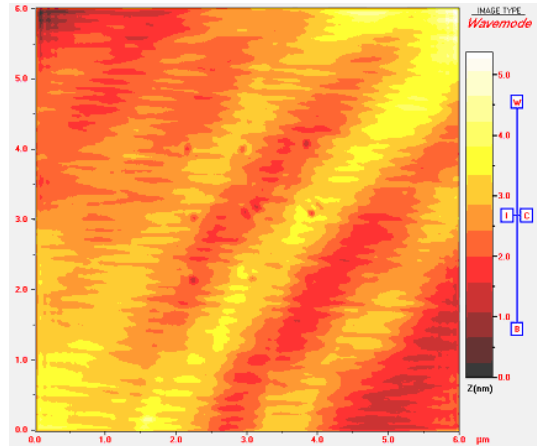


Fig 4 AFM image of hole array on GaSb substrate fabricated by AFM tip

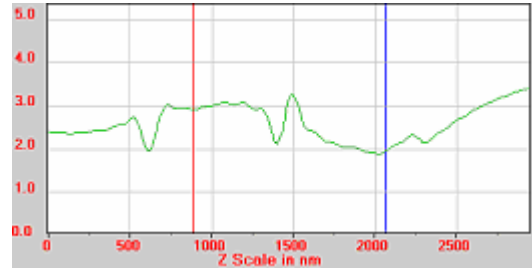


Fig 5 the dimensions of the hole on GaSb surface

3. Deposition mechanism

For gold nanodot deposition, the mechanism of atom transfer from the gold-coated AFM or SPM tip is still controversial. Some believe it to be by field evaporation, while others consider it to be by direct contact between the tip and the sample surface. A few models have been proposed, but no one has been directly proved. In our research, we demonstrate that our Cr nanodots are deposited by direct contact between the tip and the surface. The result of nano-hole array creation in the section above is used to support our model. The nine-hole array in Fig 4 is made under the same conditions by the same AFM tip that we used for Cr deposition, except with no Cr left on it. After the Cr coating on the tip is used up, we can consider the tip as a bare silicon AFM tip. When it contacts the surface during oscillation, the resistance is reduced dramatically. When a voltage is applied, the current increases suddenly, and the most power is consumed between the tip and the surface. Therefore, the temperature in the contact area increases rapidly. It may reach the molten point of GaSb or higher, whereupon the substrate in that area melts little by little over a 30 seconds period. Eventually, the hole is formed. From Fig 4 and Fig 5 we can exclude that the atoms of the substrate are evaporated to the tip by the electrical field since

the size of the holes is uniform, otherwise the tip will get larger and larger. Consequently, the hole is also getting larger and larger because of material accumulation on the tip from the substrate. Also, it is unlikely to vaporize elements of Ga and Sb due to their high boiling points. Since the process setting of hole formation is the same as that of the Cr deposition, therefore, we conclude that the Cr dots are deposited by contact. However, during the Cr deposition, holes cannot be produced. The reason is that Cr is very adhesive, and a very sharp Cr tip can be formed under the high electrical field by an electro-migration effect. Preliminary experiments have suggested that effectively one in three deposited Cr atoms is singly ionized. When this Cr tip touches the GaSb surface during the tip tapping down, an ohmic contact is formed between the Cr point and the surface; the resistance is much smaller than that between the sample and the bare silicon tip. However, it is still significant comparing with that of the rest of circuit due to the small contact area and the sensitivity of deflection of the tip. Hence, the temperature in the contact area will increase to a certain value, but it may not be high enough to melt the substrate surface. Meanwhile, the Cr moves down on the sharp tip under the influence of the field, and is transferred to the surface. In each tapping, a small amount of Cr at the end of the tip is transferred to the substrate, and a new tip is formed by the electro-migration for next contact during the following oscillation period shown in Fig 6 (c). One can imagine that the new Cr tip should be very small because the single oscillation period is about $6.25\mu\text{s}$ (the frequency is 160 kHz).

One of the differences between Cr deposition and gold deposition is the applied voltage. For gold nanodot formation, a smaller voltage (a few volts) is enough for transferring gold atoms from the tip to the sample because of its low threshold voltage. Therefore, the current flowing through the circuit is smaller and the temperature in the deposition area is relatively lower. Also, most people use silicon dioxide substrate or Si or other high molten point materials, it is hard to make holes on them in this situation. This is one of reasons that can identify if the deposition is a contact process. However, Cr has different properties. It is much more strongly adhesive, and a high electrical field is needed to move atoms from the surface of the tip to form a sharp Cr tip as shown in Fig 6 (b). This results in a larger current in the circuit. Moreover, we use GaSb substrates that have a lower molten point. Therefore, the phenomenon of the hole formation is observed easily as described in part 2 of section III. We still do not know how the nanodots are impacted by the elevated temperature, especially on the oxidation of dot surface. This may be our next research project.

Based on this mechanism, it is possible to obtain small clusters of Cr by controlling the deposition time and the voltage to form a sharp Cr tip. The challenge is that we need to prepare a better sample surface and use a sharper Cr-coated AFM tip to improve image resolution.

IV. CONCLUSION

In this paper, we reported the Cr nanodot formation for the first time with a Cr-coated AFM tip. We concluded that the deposition is a contact process. This mechanism is supported by the observation of formation of nanoholes. We think the size of nanodots is able to be controlled by applying a proper voltage and deposition time. This approach can also be used to fabricate nanolines and wires on a substrate.

V. REFERENCE

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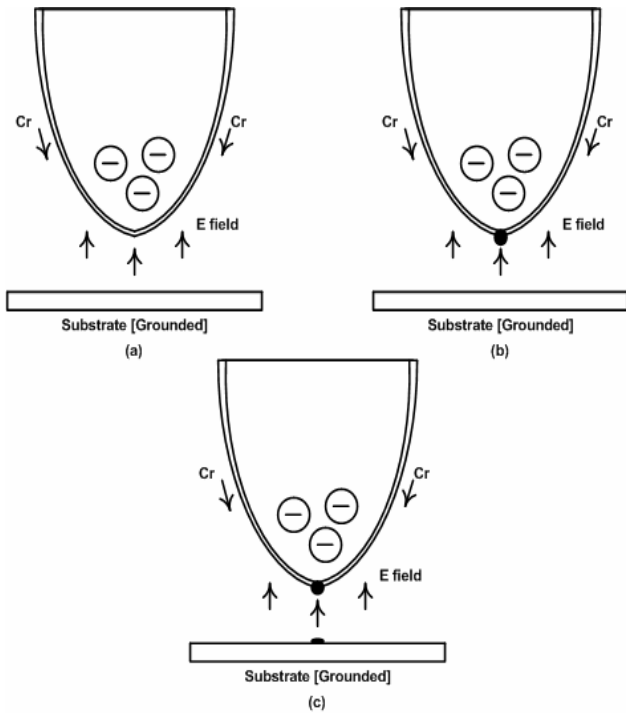


Fig 6 Schematics for Cr atom transfer to the substrate (a) initial state (b) sharp Cr tip formation (c) after deposition

