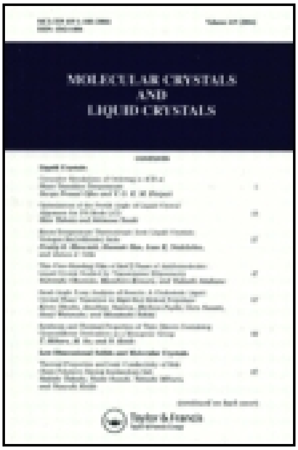


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# Nanometer Scale Current-Voltage Charcteristics of $C_{60}$ Films

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# Nanometer Scale Current-Voltage Charcteristics of $C_{60}$ Films

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The current-voltage characteristics of $C_{60}$ films in nanometer scale are investigated by using atomic force microscope (AFM) with a conductive cantilever. The results can be explained by energy band theory assuming vacuum level alignment.

*Keywords:* $C_{60}$ films; AFM; current-voltage characteristics; interface

## INTRODUCTION

Applications of molecular materials to optoelectronic devices are of practical significance [1-3]. With the discovery of fullerences, a completely new family of molecules became available whose properties were expected to be very unusual due to the fact that they were made only of carbon and had cage-like structures [4, 5]. Studies have shown that solid $C_{60}$, in particular, has many interesting properties such as conductivity, superconductivity [6-7]. In addition, because of its high stability and relatively strong intermolecular interactions, $C_{60}$ is suitable for thin film preparation.

The motivation to fabricate integrated circuits of ever increasing density will require the measurement of electrical properties with both lateral and vertical resolution approaching 10 nm or better. The electrical current $I$ flowing as a function of tip displacement $s$ towards an individual $C_{60}$ molecule is investigated by scanning tunneling microscopy (STM) [8]. The investigation on the metal-vacuum-semiconductor junction structure by STM has shown that variations in tunneling characteristics on an atomic scale can be detected. There is no report of the nanometer scale electrical properties of ultra-thin $C_{60}$ films by AFM. In this paper, we describe studies of the electrical characteristics of $C_{60}$ films on different substrate ($MoS_2$, HOPG, Au(111)) by AFM with a conductive cantilever. The information obtained by AFM is related to the $C_{60}$ films and the interface between the $C_{60}$ films and the substrate with near atomic or nanometer resolution.

## EXPERIMENTAL DETAILS

The commercially available $C_{60}$ powder was degassed at 200°C in high level vacuum ($10^{-6}$ Pa) for 10 hours before use. The $C_{60}$ powder was introduced into a molecular beam epitaxy (MBE) apparatus with a base pressure of about $1 \times 10^{-7}$ Pa. The thickness of films was monitored with a quartz crystal oscillator. The thickness of $C_{60}$ thin films ranges from a monolayer to 5 layers generally grown at a rate of 0.2 nm/min. The $MoS_2$, HOPG substrates were cleaved in air and immediately transferred into the vacuum chamber. The epitaxial film of Au(111) was prepared on mica and transferred into the MBE system without exposed to the air.

The topography observation and current-voltage measurement of the $C_{60}$ thin films were carried out by using a SPM unit SPI-3700 (Seiko Elect. Ind. Co.) at ambient environment. For the topography observation, contact mode AFM was employed with a commercial gold-coated cantilever (The resonance frequency was 14 kHz and spring constant was 0.22 N/m). The current-voltage characteristics were obtained by applying DC voltage to the sample surface through the conductive cantilever. The sample was connected electrically to a metal sample stage by conductive paste. All the images shown in this paper are original data only with tilting treatment.

## RESULTS AND DISCUSSION

Figure 1(a) shows the contact mode AFM image of $C_{60}$ grains deposited on a Au(111) substrate. Au(111) substrate makes up of about 1 $\mu$m large islands and about 200 nm small islands. Although $C_{60}$ forms island on Au(111) too, they can be distinguished from Au(111) substrate by the grains size. The average size of $C_{60}$ islands was in the range of 50-100 nm. Current-voltage characteristics can be measured at different locations in the image, as indicated in figure 1(b). Curve 4 and 5 show the conductivity of the Au(111) substrate at different location. The difference between the two curves is due to the interface between the large island (curve 5) and the small island (curve 4). The current-voltage curves of $C_{60}$ grains (curve 1, 2 and 3) show Schottky behavior which indicates the formation of Schottky contact between substrate Au(111) and $C_{60}$ grains.

Figure 2(a) indicates the AFM image of $C_{60}$ multilayers on HOPG substrate. It can be found that the isolated grains have been formed on the substrates, most of these grains are monolayer, however, the second layer appears in some regions. The current-voltage characteristics can be measured at different locations in the image, as indicated in figure 2(b). The current-voltage curve of the bare substrate (curve 1) shows Ohmic behavior. The current-voltage curves obtained at the $C_{60}$ grains (curve 2, 3) show a linear voltage dependence characteristic of Ohmic behavior at low applied voltages ($|V| \leqq 0.4$ V). For larger voltage, the exponential dependence dominates the I-V characteristic. The currents at $C_{60}$ grains are lower than that of bare HOPG substrate at the same applied voltages.

Figure 3(a) shows the AFM image of $C_{60}$ multilayers on $MoS_2$ substrate. It can be found that isolated grains have been formed on the substrates, most of these grains are the first layer, however, the second, third layer appears in some regions. Current-voltage characteristics can be measured at different locations in the image, as indicated in figure 3(b). The current-voltage curve of bare substrate (curve 1) shows rectification behavior. The current-voltage curves obtained at the $C_{60}$ monolayer and multilayers (curve 2, 3) show the formation of a barrier of semiconductor-semiconductor contact between substrate $MoS_2$ and $C_{60}$ grains. The currents at $C_{60}$ grains are lower than that of bare $MoS_2$ substrate at the same applied voltages. For the current through the first layer (curve 1) and the multilayers (curve 3), lower currents are obtained through the multilayers. The decrease of the current value due to the increase of the thickness of the $C_{60}$ thin films results from the resistance of $C_{60}$ thin films as an n-type semiconductor.

From the viewpoint of energy band, the center of the HOMO-LUMO gap of $C_{60}$ is 4.8 eV [9], the Fermi level for Au(111) is 5.31 eV, the Fermi level for HOPG is 4.5 eV and the Fermi level for $MoS_2$ is 5.2 eV [10]. When $C_{60}$ films deposited on Au(111), HOPG and $MoS_2$ substrate respectively, a Schottky barrier will form between $C_{60}$ films and Au(111) substrate, no barrier will form between $C_{60}$ and HOPG substrate and a barrier will form between $C_{60}$ and $MoS_2$ substrate assuming vacuum level alignment.

## CONCLUSIONS

From the results and discussion in the previous paragraph, the nanometer scale electrical characteristics of $C_{60}$ films and the interface between $C_{60}$ films and substrate can be obtained by AFM. The current-voltage measurements on the monolayer or multilayer $C_{60}$ thin films indicate that its operation characteristics can be qualitatively described by the conventional energy band theory assuming vacuum level alignment.

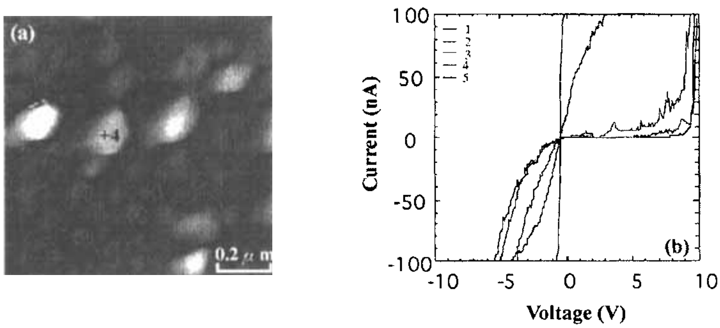


**Fig. 1 Topography (a) and I-V curves (b) of $C_{60}$ growth on Au(111)**

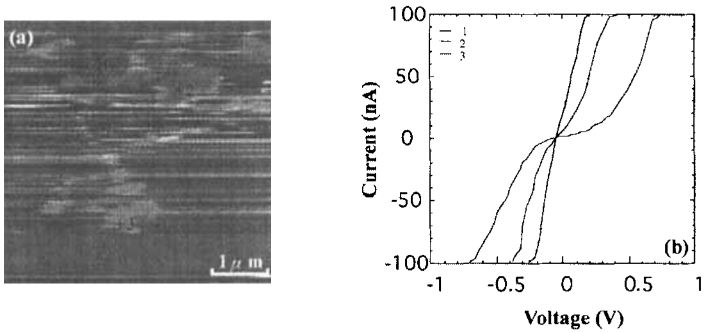


**Fig. 2 Topography (a) and I-V curves (b) of $C_{60}$ growth on HOPG**

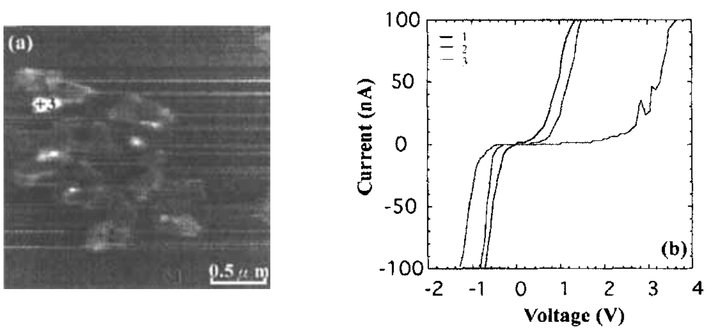


**Fig. 3 Topography (a) and I-V curves (b) of $C_{60}$ growth on $MoS_2$**

**See color plate XVIII at the back of this issue.**

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