

Hot wall epitaxial growth of highly ordered organic epilayers

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Abstract

Hot wall epitaxy works close to thermodynamic equilibrium and is therefore most applicable for materials with Van der Waals binding character. The hot wall epitaxy system can be described as semiclosed growth reactor, consisting of a vertically mounted quartz cylinder, which is heated by three separately controllable ovens, and is closed on top by the substrate. The first oven heats the source material and controls the growth rate. The second heats the hot wall between source and substrate, which guaranties the closed character of the reactor and helps to avoid loss of valuable material. The third oven controls the substrate temperature and allows to influence the growth process on the substrate surface.

We achieved crystalline perfection for C₆₀ layers on mica substrates and fabricated Ba-doped n-type layers with mobilities of 6000 cm²/V s at room temperature.

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1. Introduction

Research on conjugated organic systems is a rapidly expanding field at the turn of chemistry, condensed matter physics, materials science and device physics due to the promising opportunities for applications of these π -electron semiconductors in electronics and photonics. Due to their interdisciplinarity, this class of materials attracted the attention of a large number of researchers and originated the beginning of a revolution in “Organic Electronics”. Starting with an initial focus on the p- and n-doping of conjugated oligomers and polymers, the unique electrochemical behavior of these technological important materials enabled the development of cheap sensors. Because of the progress toward better developed materials with higher order and purity, these organic materials are now also available for “organic electronic” devices. More generally, organic electronics includes now diodes, photodiodes, photovoltaic cells, light emitting diodes, lasers, field effect transistors, electro-optical couplers and all organic integrated circuits and claims thereupon for key technology of the 21st century [1–3].

The area of conjugated organic semiconductors can be divided into two large parts: conjugated polymers and small

conjugated organic molecules. Conjugated polymers combine properties of classical semiconductors with the inherent processing advantages of plastics and therefore play a major role in low cost, large area optoelectronic applications [4–6]. Unfortunately, polymer films are commonly highly disordered in the solid state and, consequently, show low charge carrier mobilities because of strong Anderson localization [7]. Therefore, an inherent part of research in the field of organic electronics focuses on small molecule systems, in which highly ordered crystalline structures can be achieved—in contrast to the disordered, often amorphous phases of the polymers. These molecules are additionally thermally stable up to 300–400 °C, are obtained as pure materials and processed in high-vacuum or ultra high-vacuum conditions [8,9]. The recent demonstration of effective optoelectronic devices based on molecular single-crystals like pentacene or C₆₀ [10,11] has clearly shown the advantages of this “small molecule approach” and has received widespread attention. Further development of such devices requires using of epitaxially grown, highly crystalline thin films with well-defined orientation of the molecules. Unfortunately, up to now the physical properties of molecular thin films do not compare favorable to those of single-crystal materials. There is a large number of papers about significant influence of structural order on the performance of thin film devices based on small molecules [12,13]. In particular, the recent emphasis in research of conjugated

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oligomer films is founded in the correlation between the electronic structure [14] and charge transport through the active layer [15]. These studies are motivated by their implications on charge transport in organic field effect transistors (OFETs). It has been demonstrated (mostly for α -sexithiophene films) that the carrier mobility in OFETs can be significantly improved if the degree of order in all the film increases [16]. The correlation between degree of order and carrier mobility was also found for thin film structures based on other molecules [17]. High order, implying enhanced charge carrier transport are also of major importance in other organic electronic devices: photodetectors and photovoltaic devices [18,19] and LEDs [20].

In addition to chances in device performance, well-ordered or single-crystalline molecular films allow the investigation of anisotropic optical and electronic properties of π -conjugated systems [21,22] as it was found in bulk crystals [8–11]. It should be mentioned here that such phenomena are commonly not observed in conjugated polymer thin films, which are usually disordered. Therefore, such investigations are also of considerable fundamental interest. The challenging task for the future is to grow epitaxial layers of high crystalline quality. The main difference between organic and inorganic materials with respect to epitaxial growth is the different nature of bonds. The inorganic materials are first physisorbed and then chemisorbed on the growing surface. In the case of organic materials only physisorption occurs because no chemical bonds are formed between the molecules. As a result, the growth process is governed by very weak bonds of Van der Waals' type reflected by a very small sticking coefficient. That means that epitaxial growth of organic materials is performed usually at comparable low temperatures. Many attempts were made so far to grow organic materials on inert surfaces mainly by MBE. An extended overview can be found in [23]. As growth method MBE offers the advantage of in situ monitoring. On the other hand, growth occurs in an open system far away from thermodynamic equilibrium.

Especially in the case of Van der Waals epitaxy it is a distinct advantage to use a growth method which works as close as possible to thermodynamic equilibrium, which allows to grow at relatively high vapor pressures of the organic material in the region of the substrate where the deposition occurs.

2. Experimental set-up

A growth method which satisfies the conditions for Van der Waals epitaxy is the so called hot wall beam epitaxy (HWBE) [24]. In contrast to a molecular beam epitaxy (MBE) system, HWBE uses the near field distribution of effusing molecules at the orifice of an effusion cell [25]. The substrate can also be used to close the tube of the source like a lid forming a semiclosed growth system, which is then known as hot wall epitaxy (HWE) [26]. HWE is proved as a very successful growth method for organic materials like C_{60} [27,28] and its Ba-containing compounds [29]. A quartz tube, with the source material at the bottom and the substrate on the top closing it tight with respect to the mean free path of the evaporated source molecules, is placed with three separated heaters into a high-vacuum chamber. The region of the growth reactor between source and substrate, called hot wall, guarantees a nearly uniform and isotropic flux of the molecules onto the substrate surface. The advantage of such closed system is the minimization of source material losses, which can be very important in case of new organic materials which are not commercially available. To perform the doping experiments with Ba a slight modification of the HWE system was necessary to add to the usual growth reactor a second evaporation source for doping material. A schematic cross-section of the improved HWE system can be seen in Fig. 1 together with a typical temperature profile along the quartz tube. The Ba-doping source is contained in a concentric quartz ampoule and heated separately by oven 2. In that way the partial pressure of C_{60} and Ba could be

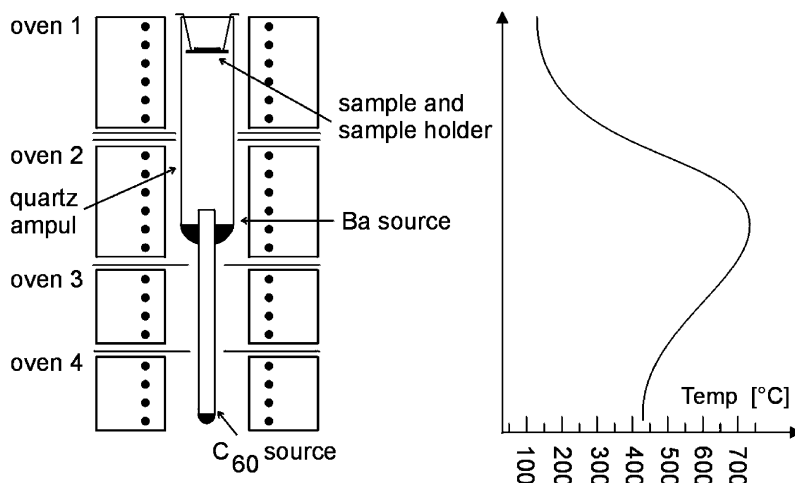


Fig. 1. Schematic cross-section of the HWE reactor to grow Ba-doped C_{60} films together with a typical temperature profile.

controlled independently. The used C_{60} source material was at first 99.4% pure. It had to be cleaned from solvents and impurities by subliming the material three times at $550\text{ }^{\circ}\text{C}$ under dynamical vacuum of 1×10^{-6} mbar and by protecting it from visible light in order to minimize photo-induced polymerization. About 200 mg of the cleaned material was loaded into the HWE system, which was enough to fabricate more than 50 epilayers with an area of 1 cm^2 and an average thickness of 200 nm. The Ba-doping material was loaded in a glove box under nitrogen atmosphere into the quartz ampoule to avoid any oxidation.

As substrate material, sheets of mica were used because of the inert character of freshly cleaved surfaces, free of unsaturated bonds which is in favor for Van der Waals epitaxy. The top most layer of mica consists of potassium atoms forming a hexagonal grid with a periodicity which is close to the diameter of C_{60} molecules. Consequently epitaxial growth of C_{60} on mica should be initiated in the (1 1 1) direction. The mica sheets were cut into pieces ($15\text{ mm} \times 15\text{ mm}$), cleaved in air with an adhesive tape, and immediately transferred into the vacuum chamber of the HWE system. The substrates, before being transferred into the growth reactor, were preheated in the HWE chamber for 1 h at $400\text{ }^{\circ}\text{C}$ in a separate oven to remove adhesives from the substrate surface.

To grow pristine C_{60} epilayers, the substrate temperature was varied from 100 to $200\text{ }^{\circ}\text{C}$, and the wall temperature from 340 to $440\text{ }^{\circ}\text{C}$. Out of this wide range of temperatures a set was selected which gave the best crystalline quality. The influence of the substrate temperature on the growth and crystalline quality of C_{60} films was studied by varying the substrate temperature at a fixed source and wall temperature of $400\text{ }^{\circ}\text{C}$.

3. Results and discussion

X-ray diffraction experiments were performed to test the crystallographic orientation of the layers. Usual $\omega/2\theta$ scans showed only the (1 1 1) reflex of C_{60} and its higher orders and pole figure measurements proved the in plane orientation of the epilayers [29]. The FWHM of the X-ray rocking curves was used as criterion for the crystalline quality.

In Fig. 2, the rocking curve FWHM of the (1 1 1) reflex of C_{60} films, which are about 120 nm thick, is plotted as a function of T_{sub} . Regarding temperatures between 100 and $200\text{ }^{\circ}\text{C}$, the C_{60} film grown at $140\text{ }^{\circ}\text{C}$ has a minimal FWHM of 200 ± 20 arcs, indicating an nearly perfect monocrystalline growth. For lower temperatures, there is a gentle increase of the FWHM, whereas for higher temperatures, a significant jump can be observed between 180 and $200\text{ }^{\circ}\text{C}$. The 120 nm thick films grown at T_{sub} between 100 and $180\text{ }^{\circ}\text{C}$ exhibit a narrow Gaussian shape as shown in the inset of Fig. 2.

The additional installed annealing oven allowed to perform post growth annealing processes without breaking the

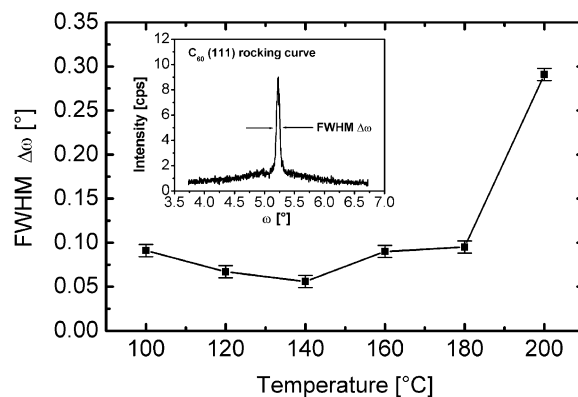


Fig. 2. FWHM of the C_{60} (1 1 1) rocking curve vs. the applied substrate temperature.

vacuum. The improvement in crystalline quality of the C_{60} epilayers by annealing was investigated by HRXD. Typical rocking curves of an as-grown and an annealed C_{60} layer of the same thickness of 100 nm are compared in Fig. 3. The FWHM of the as-grown layer is 240 arcs, comparable with the results reported above. The improvement of the annealed layer, which was baked 20 min at a temperature of $130\text{ }^{\circ}\text{C}$, is documented by the decrease of the FWHM to 140 arcs and the increase of the peak intensity. The crystalline quality of the annealed C_{60} was also tested by pole-figure measurements. Six sharp maxima indicated twin formation, however, the sharpness of the peaks, and the very low background signal were a clear indication of the high crystalline quality.

For all doping experiments, the C_{60} source temperature and the substrate temperature were kept constant at 400 and $140\text{ }^{\circ}\text{C}$, respectively. To study the incorporation of Ba we varied the Ba source temperature between 470 and $750\text{ }^{\circ}\text{C}$, resulting in Ba_xC_{60} compound layers. It is very important to notice that as soon as Ba was used in the growth reactor, the

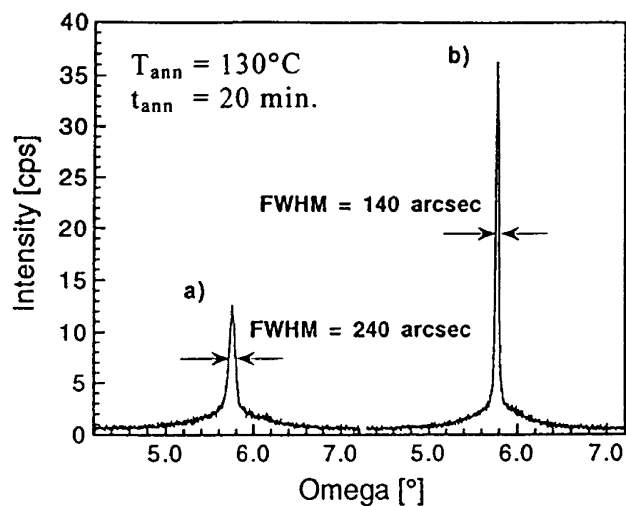


Fig. 3. X-ray rocking curve for (a) as-grown and (b) annealed C_{60} layers. The annealing time and temperature are inserted.

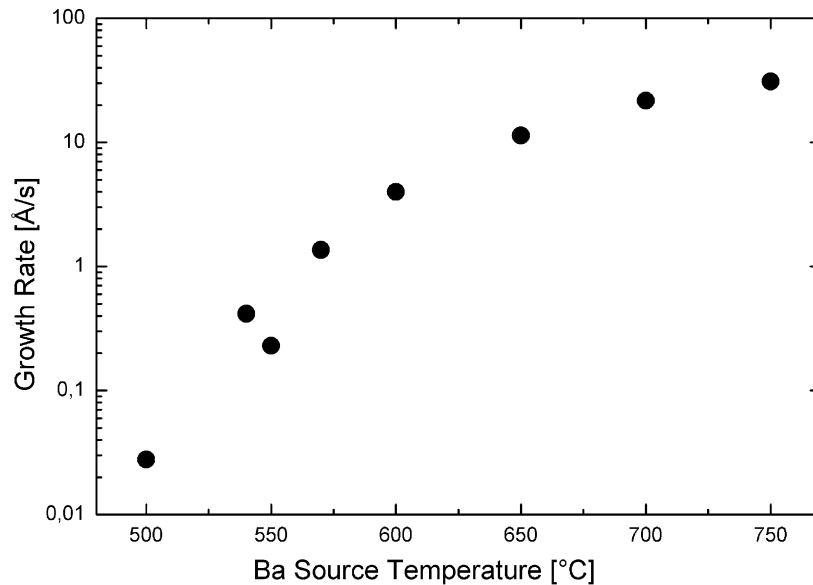


Fig. 4. Growth rate of the Ba-doped C_{60} layers as a function of the Ba source temperature.

growth rate of the C_{60} layers was mainly controlled by the Ba source temperature and only slightly dependent on the C_{60} vapor pressure. Fig. 4 shows the average growth rate of Ba-doped C_{60} layers which were grown for 7 h. For Ba source temperatures smaller than 600 °C, the results follow an exponential function: for higher Ba temperatures a saturation can be observed. This behavior can be interpreted by the assumption that the incorporated Ba causes a charge transfer to C_{60} [30] and controls the sticking coefficient for the C_{60} molecules that are always present in a surplus in the vapor. However, when the surface coverage of Ba is saturated, the growth rate also cannot be increased further. In that way the growth mechanism changes from Van der Waals epitaxy, which is typical of pure fullerenes, to a different

mechanism resulting from a stronger bonding type evoked by the charge transfer.

The resistivity of the Ba-doped layers was measured in situ by a four-point probe without breaking the vacuum. We found, that the resistivity depends only on the applied Ba source temperature. For Ba source temperatures smaller than 600 °C an exponential decrease of the resistivity can be observed. For larger Ba source temperatures a saturation is observed. We conclude, that for Ba source temperatures larger than 600 °C the growing surface is saturated with Ba atoms and consequently no further incorporation and decrease in resistivity can be achieved. It is worthwhile to notice, that the growth rate (Fig. 4) and the resistivity show the same trends. For Ba source temperatures below 520 °C

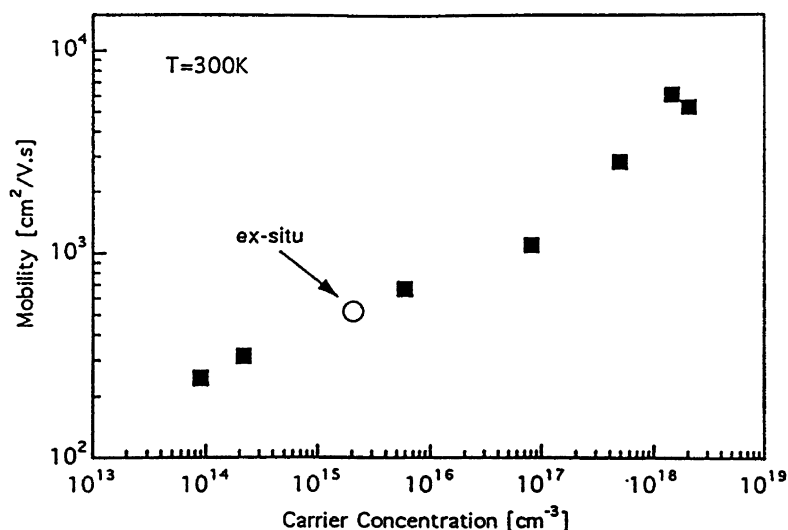


Fig. 5. Carrier mobility as a function of n-type carrier concentration. For comparison the ex situ measured data point is given by an open circle.

the growth rate and the resistivity are comparable to pristine C₆₀ layers, which means, that the Ba partial pressure is too low to obtain an effective Ba incorporation, and consequently no charge transfer occurs, resulting in an increase of growth rate or decrease of resistivity. Also the typical saturation behavior is observed in growth rate and resistivity beyond a Ba source temperatures of 600 °C, which can be interpreted as a limitation in the Ba incorporation rate at electrical active sites.

Nothing was known so far about the carrier concentration or the mobility of carriers in Ba containing C₆₀ layers. We installed a permanent magnet with a magnetic field of 0.43 T in the vacuum chamber of the HWE system and realized the possibility of measuring Hall effect on Ba_xC₆₀ epilayers. The sample holder with the necessary wiring and the contacted Ba_xC₆₀ layer could be transferred from the HWE growth reactor to the permanent magnet. The evaluation of the data gave n-type conductivity with a carrier concentration between 10¹³ and 10¹⁸ cm⁻³. For Ba source temperatures larger than 600 °C the carrier concentration saturated around 2 × 10¹⁸ cm⁻³, which fits very well into the picture obtained from the growth rate and the resistivity measurements.

Even more surprising were the data obtained for the mobility of the carriers that are much higher than expected. The mobility measured for each sample is shown in Fig. 5 as a function of the obtained carrier concentration. The maximum measured mobility was 6000 cm²/V s, which is to our knowledge the largest mobility reported in literature so far. To verify our experimental results we performed in addition to the Hall effect measurements magneto resistance measurements, which gave in all experiments the same results within an experimental error of 5% in comparison to the data obtained from Hall effect.

To prove our in situ measurements we fabricated a sandwich structure by covering the Ba_xC₆₀ with pristine C₆₀. So we could expose this sandwich structure to ambient air and transfer the layer to a standard ex situ Hall effect equipment. The obtained result is shown in Fig. 5 labeled with “ex situ”. The excellent alignment with the data obtained from in-situ measurements was very convincing for the reliability of the data obtained before.

4. Conclusions

We have shown, that HWE is an appropriate method for growing C₆₀ and Ba doped C₆₀ epilayers. The excellent crystalline quality of the epilayers could be further improved by in situ annealing processes, resulting in a FWHM of the X-ray rocking curve of 140 arcs. The incorporation of Ba in the C₆₀ layers caused a significant charge transfer from the Ba atoms to the C₆₀ molecules, resulting in an increase of the

growth rate and an n-type conductivity of the doped layers with enormously high mobility of the charge carriers.

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