Electronic transport properties in irradiated C$_{60}$ FNW

Tatsuya Doi$^1$, Yasuto Chiba$^1$, Hajime Tsuji$^1$, Misaki Ueno$^1$, Shih-Ren Chen$^{1,2}$, Nobuyuki Aoki$^1$, and Yuichi Ochiai$^1$

$^1$Chiba University, Department of Advanced Integration Science, 1-33 Yayoi, Inage-Ku, Chiba 263-8522, Japan
Phone: +81-43-290-3430 E-mail: doitatuya@graduate.chiba-u.jp

$^2$Southern Taiwan University of Technology, Tainan 710, Taiwan

1. Introduction
As for near future electronics devices, there exist many attractive topics for nano-carbon materials, especially, for carbon nano-tubes and C$_{60}$ crystalline whiskers. Since the first report in 1993 [1], several trials on the polymerization due to photo irradiation have been proposed [2-4]. Especially, photo- and electron-beam irradiation are the easy and area selectable method, therefore they have possibility to fabricate the C$_{60}$-based carbon nanodevices. However, most of them have not been yet examined on detailed electronic transport properties. In this paper, we are discussing the effect of photo-irradiations on the electronic transport properties of C$_{60}$ fullerene nano-whisker (FNW), by investigating the field-effect transistor (FET). Furthermore, the morphology of photo-irradiated C$_{60}$ FNW was observed by scanning electron microscope (SEM).

2. Experimental details
We have investigated the photo-, ultrasonic wave- and microwave- irradiation effects on the electronic transport properties of C$_{60}$ fullerene nano-whiskers (FNW), fine crystalline wires of C$_{60}$ as shown in Fig. 1. It has been studied by observing FET characteristics. In our previous research in thin film of C$_{60}$, it was clarified that the electrodes for the top contact blocked off the UV-light and polymerization was obstructed underneath the electrodes [5]. Therefore, our C$_{60}$ FNW-FETs were as a bottom-contact configuration, while top-contact organic-FET tends to exhibit good performance compared with bottom-contact structure. The C$_{60}$ FNW-FETs were fabricated with a bottom-contact configuration on heavily $p$-doped Si substrates. Si substrate with a 600 nm thick SiO$_2$ (as the gate insulator) also serve as the gate electrode. Ti/Au electrodes (20 nm/80 nm thickness respectively) for source and drain were deposited on the Si substrate by electron-beam evaporation. The channel length ($L$) was 10 $\mu$m and the channel width $W$ was 1.0 mm. Subsequently, several C$_{60}$ FNWs were put on the electrodes by resistive heating with the substrate temperature kept at 440 K. Photo-irradiation was performed about 10 hours using the UV-visible light for photolithography at pressure of $\sim$10$^6$ Torr. Substrate temperature was kept at 300 K during exposure in order to prevent the high temperature (HT) heating arise during photo-irradiation, because polymerized-C$_{60}$ induced by photo-irradiation return to C$_{60}$ monomer by HT heating. The existence of polymerized-C$_{60}$ was confirmed by investigating the solubility in toluene, because C$_{60}$ become insoluble in organic solvent by polymerization. The electrical measurements were performed in the vacuum ($\sim$10$^6$ Torr) as long as there is no description.

3. Results and discussion
Source-drain current ($I_{SD}$) versus source-drain voltage ($V_{SD}$) characteristics ($I_{SD}$-$V_{SD}$) at several back-gate voltages ($V_G$) before annealing are shown in Fig. 2 (a) and (b) before and after photo-irradiation, respectively. The field-effect mobilities ($\mu$) estimated by fitting the linear region of the $I_{SD}$-$V_{SD}$ characteristics are $3.1 \times 10^{-4}$ cm$^2$/V$s$ and $2.6 \times 10^{-5}$ cm$^2$/V$s$ before and after photo-irradiation, respectively. From these results, it has been understood that $I_{SD}$ and field-effect mobility ($\mu$) decreased by about one order after the irradiation. Based on the source-drain current on gate voltage ($I_{SD}$-$V_G$ at $V_{SD} = 10$ V) for both before and after photo-irradiations, it is found that the threshold-voltage ($V_T$) shows to be lowered by photo-irradiation as well as in C$_{60}$ thin film FET [5]. This result indicates that the injection barrier between Au electrode and C$_{60}$ has been changed by photo-polymerization and let to make easy on the carrier injections. However, we have no FET working after exposing the atmosphere but the irradiated effect in C$_{60}$ thin film FET device shows clear I-V characteristics even in after exposing, although the source-drain current value is lower about $10^{-3}$-$10^{-4}$ times.

Fig. 1. The SEM photograph of the C$_{60}$ FNW.
Fig. 2. $I_{SD}$-$V_{SD}$ characteristics of the C$_{60}$ FNW-FET for before (a) and after photo-irradiations (b) are shown, the $V_G$ is varied from 0 to 30 V and the mobility decreases by about one order of magnitude after the irradiation.

Finally, the morphology of our C$_{60}$ FNW after photo-irradiation was investigated using SEM. As a result of the comparing before and after irradiations, a certain small cracks were observed in the case of thin FNW as shown in Fig. 3 (a). These clacks are not observed in a case of the thick C$_{60}$ FNW as shown in Fig. 3 (b). It can be considered that the intermolecular distance of C$_{60}$ is shortened by the polymerization. Therefore, it may consider that this shrinkage caused by such cracks, and must consequently leads to the decrease in $I_{SD}$ and $\mu$.

4. Summary
The FET characteristics of C$_{60}$ FNW were investigated before and after photo-irradiation. It have been understood that the $I_{SD}$ clearly decreased after photo-irradiation and the $\mu$ decreased from $3.1 \times 10^{-4}$ cm$^2$/Vs to $2.6 \times 10^{-5}$ cm$^2$/Vs. Also, it has been clarified by the SEM investigation that photo-irradiated C$_{60}$ thin film has a few cracks in the case of thin wire, but in the case of thick one there is no crack. Therefore, we can not determine the origin of the decrease of $I_{SD}$ and $\mu$. After photo-irradiation, the threshold voltage seems to be lowered. Furthermore, photo-irradiated C$_{60}$ thin film shows the FET characteristics after exposure to the atmosphere, but C$_{60}$ FNW-FET does not work well in the atmosphere because O$_2$ in the air may obstruct the electron transport in C$_{60}$ devices. Therefore, we need further more studies in order to clarify the electronic transport effect on the polymerization effect on C$_{60}$ FNW-FET.

Acknowledgments
The work was supported in part by Grants-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (19054016, 16656007 and 16206001).

References