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N-channel thin-film transistors constructed on plastic by solution processes of HgSe nanocrystals

Jaewon Jang, Kyoungah Cho, Junggwon Yun, Sangsig Kim *

Department of Electrical Engineering and Institute for Nano Science, Korea University, Seoul 136-701, Republic of Korea

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ABSTRACT

We demonstrate bottom-gate thin-film transistors (TFTs) based on solution-processed HgSe nanocrystals (NCs) on plastic substrates. Solid films made of spin-coated HgSe NCs were heated at a temperature of 150 °C for 15 min to maximize the magnitude of their current, and these films were utilized as the channel layers of TFTs. A representative TFT with a bottom-gate Al_2O_3 layer operated as a depletion-mode one with an n-channel, exhibiting a field effect mobility of 3.9 cm^2/Vs and an on/off current ratio of about 10^2. In addition, the electrical characteristics of the TFT on bent substrates are briefly described.

1. Introduction

Inorganic nanocrystals (NCs) have attracted increasing attention recently in the construction of thin-film transistors (TFTs) via solution-processes for the achievement of low-cost and large-area electronics. The inorganic nanocrystal (NC)-based TFTs reported to date have yielded electrical characteristics superior to those of organic TFTs [1–3]. The solution processes used in these cases require that post activation processes be applied to the channels made of NCs [4,5]. The activation process reduces the potential barriers built in the grain boundaries, resulting in an increase in the conductivity of the channel layers. In spite of the compatibility of the solution processes of NCs with plastics, most inorganic NC-based TFTs have been fabricated not on plastic substrates, but on oxidized silicon ones, because the activation temperatures used are higher than the deformation temperatures of plastics [1–3]. Recently, solid films made of HgTe NCs were successfully activated at 150 °C, enabling the fabrication of inorganic TFTs composed of these solid films on plastics [6]. This was achieved due to the choice of HgTe NCs. The melting point of the corresponding bulk (670 °C) is lower than that of most semiconductor materials, thus making the activation temperature of the NCs compatible with plastic. The TFTs with channels made of HgTe NCs operated as p-channel ones, stimulating the construction of n-channel TFTs based on NCs on plastic substrates.

In this study, HgSe NCs were selected as channel materials for the construction of n-channel TFTs on plastic substrates. The selection of HgSe NCs was based on their following characteristics; the melting temperature (799 °C) of HgSe bulk is closer to that of HgTe bulk than those of other II-VI bulk semiconductors, HgSe NCs are well-known n-type materials, and HgSe bulk exhibits a high charge carrier mobility (15,000 cm^2/Vs for electrons at 300 K) [7]. In this paper, we first examined the conductance of solid layers made of spin-coated HgSe NCs after thermally heating them and then demonstrated the construction and electrical characteristics of bottom-gate TFTs with the HgSe NC-based channels on plastic substrates.

2. Experimental procedures

The successful construction of the TFT on a plastic substrate is achieved in this study using the following three approaches. The first is to employ UV/ozone treatment and photo-lithography for the channel isolation region. The UV/ozone treatment solves the contact problems between the hydrophilic HgSe NCs dissolved in water and hydrophobic polymer layers, and the use of conventional photo-lithography facilitates the formation of isolated NC-based active layer regions by a spin-coating process and lift-off process. Secondly, the TFT channel made of HgSe NCs was activated at a low temperature compatible with plastics. The last is our choice of the ALD process for the deposition of the gate layer. The deposition temperature of the ALD process is lower than the glass-transition or thermal decomposition temperature of the plastic substrates.

HgSe NCs were synthesized in aqueous solution by the colloidal method [8]. $Hg(ClO_4)_2 6H_2O$ of 1.97 g were dissolved in 250 ml of de-ionized water, and 1 ml of 1-thioglycerol used as a capping agent was added to the solution at room temperature. Then, the

* Corresponding author. Fax: +82 2 3290 3894.
E-mail address: sangsig@korea.ac.kr (S. Kim).

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pH of the solution was adjusted to 11.4 with 1 M NaOH. From the reaction of 0.2 g of Al_2Se_3 and 75 ml of 4 M HCl placed in separate three-neck flasks, H_2Se gas was generated and passed through the solution of $Hg(ClO_4)_26H_2O$ and 1-thioglycerol. HgSe NC powders were obtained by centrifuging after adding 2-propanol as a precipitant. The obtained powders were washed with acetone and methanol to remove the organic capping materials. The HgSe NC powders were re-dispersed in water to use as a spin-coating solution for a channel layer.

Poly-ether-sulfone (PES) coated with cross-linked poly-4-vinlyphenol (C-PVP) was used as a plastic substrate. UV/ozone treatment was employed to make the surface of the C-PVP buffer layers hydrophilic [9,10]. A HgSe NC layer was spin-coated on top of the UV-treated substrate in air. Two gold electrodes with a channel length of 1 mm and a channel width of 1 cm were formed on the spin-coated HgSe NC layer to examine the dependence of its conduction on the heating temperature.

An Al_2O_3 bottom-gate TFT was fabricated on a C-PVP coated PES substrate, as follows. A gold gate electrode was deposited by a thermal evaporator. A 50 nm thick Al_2O_3 dielectric layer was deposited on a C-PVP coated PES substrate at 150 °C for 180 min by the atomic layer deposition (ALD) method. An isolated HgSe NC-based channel layer was then created by a spin-coating process and lift-off process. The HgSe NC channel layer was heated in a vacuum at 150 °C for 15 min. Subsequently, two gold source and drain electrodes with a channel width of 300 μm and a channel length of 20 μm were formed by the thermal evaporation (see Fig. 3a).

The synthesis of the HgSe NCs was confirmed by high resolution transmission electron microscope (HRTEM: FEI Technai G2 F30). The structural properties of the HgSe NCs were analyzed by X-ray diffraction (XRD: RIGAKU, D/MAX IIA with Cu Kα radiation). *I–V* curves were measured for the fabricated TFT with an Agilent 4155C semiconductor parameter analyzer and a four probe station at room temperature in air.

3. Results and discussion

The XRD patterns taken from a solid film made of the as-synthesized HgSe NCs matched well with the lines drawn on the base of the standard JCDPS card (080469) of bulk HgSe (Fig. 1). The broadening of the XRD peaks originates from the nanometer scaled diminution of the crystallite sizes; the as-synthesized HgSe NCs were spherical in shape with an average diameter of about 5 nm (the inset of Fig. 1).

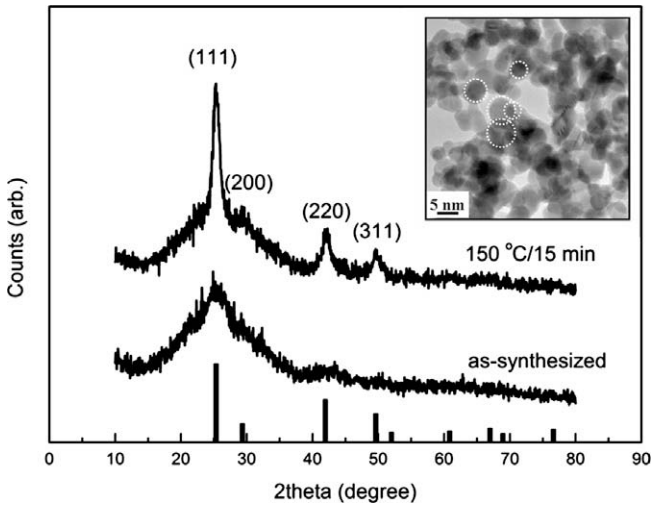

Fig. 1. XRD patterns of the as-synthesized and heated HgSe NCs. The inset shows the HRTEM image of the synthesized HgSe NCs.

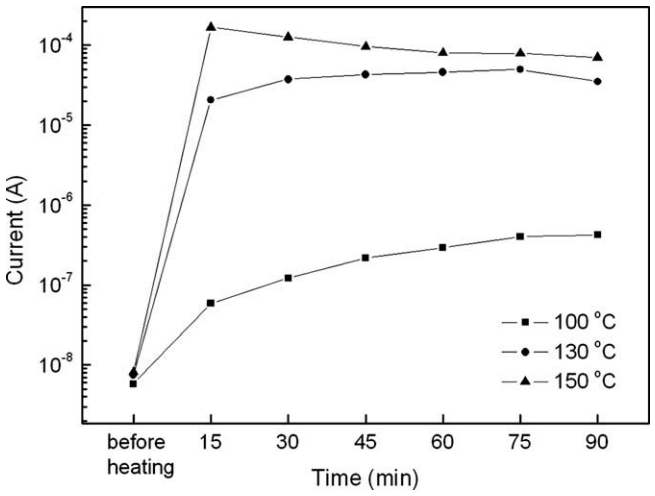

Fig. 2. Current measured at 10 V for channel layers made of HgSe NCs heated at selected temperatures.

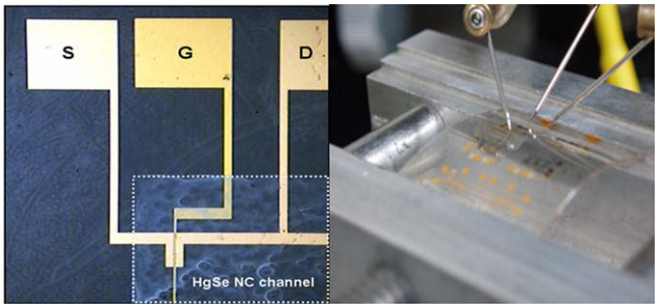

Fig. 3. Top-view image of a HgSe NC-based TFT with a bottom-gate Al_2O_3 dielectric layer (left-side) and photographic image of the measurement (right-side).

The activation process for the solid film at 150 °C for 15 min makes the widths of the XRD peaks narrower, indicating that the grain size of the HgSe NCs in the solid film becomes larger, compared with that of the as-synthesized NCs. The grain size of the heated NCs is estimated to be about 15 nm from the extraction of the widths of the XRD peaks [11].

The magnitude of the current measured for the HgSe NC channel heated thermally is plotted as a function of the heating time in Fig. 2. The current of the channel heated for 15 min is remarkably enhanced in magnitude, compared with that of the channel made of the as-synthesized NCs. As the heating time increases above 15 min, the current is gradually enhanced in magnitude for the channel layer heated at 100 and 130 °C, and it is gradually decreased for the channel layer heated at 150 °C. The enhancement of the current magnitude is associated not only with the enlargement of the sizes of the NCs, but also with the necking of the NCs. The enlargement of the sizes of the NCs already confirmed by the XRD patterns (shown in Fig. 1) reduces the number of grain boundaries in the channel between the two electrodes, and the necking of the NCs lowers the height of the potential barriers between the boundaries [12]. Both the reduction in the number of grain boundaries and the lowering of the height of the potential barriers improve the transportation of charge carriers in the channel. The gradual decrease in the magnitude of the current for the channel layer heated at 150 °C for heating times longer than 15 min could be due either to the evaporation of the NCs or to the cracking of the channel layer by thermal shocking. It is worth noting that, for the channel layer heated at temperatures higher than 150 °C, no current was measurable. However, it has been reported in Ref. [13] that HgSe NCs with