C-6-1(Invited)

Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp692-693

Carbon nanotube-based plastic electronics

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1. Introduction

Flexible devices fabricated on a plastic film are attracting much attention because of the potential to open new market for electronics. Among various kinds of semiconductor materials, carbon nanotubes can provide high-performance devices on plastic films at low cost. In this work, our recent results on carbon nanotube-based plastic electronics will be presented such as the carbon nanotube thin-film transistors (TFTs) and integrated circuits (ICs) realized on a transparent plastic film [1]. The high-throughput flexographic printing process to fabricate carbon nanotube TFTs will also be introduced.

2. Fabrication of high-performance carbon nanotube TFTs and ICs on plastic substrate

We developed the simple technique to form uniform carbon nanotube thin film on a plastic film based on the gas-phase filtration and transfer process [1]. Carbon nanotubes were grown by a floating-catalyst CVD technique with CO as the carbon source, wherein catalyst particles were produced by decomposition of ferrocene vapor [2], as shown in Fig. 1. The carbon nanotube network was collected by filtering through membrane filters of cellulose acetate mixed with nitrocellulose at room temperature. The carbon nanotube network was transferred from a membrane filter to the substrate with electrodes of TFTs by dissolving the filter in acetone. An SEM image of typical carbon nanotube thin-film is shown in Fig. 1. The density of carbon nanotubes was 0.18 μm^{-2} for the collection time of 2 sec.

Figure 2 shows the characteristics of a TFT fabricated on a Si substrate based on the gas-phase filtration and transfer process. The channel length and width were 100 μm each. Even though the carbon nanotube thin-film contains both metallic and semiconducting carbon nanotubes, the TFTs show good pinch-off characteristics. The on/off ratio is $6x10^6$ at V_{DS} = -0.5 V (typically $>10^6$). The mobility was evaluated from the transconductance in the linear region to be 634 cm^2/Vs. Here, the gate capacitance was estimated by Cao's model that takes into account the electric force lines focusing onto carbon nanotubes [3].

Figure 3 shows (a) a photograph of ICs fabricated on a transparent plastic film, (b) schematic of a TFT, and (c) the input-output characteristics of an inverter. In this study, we use polyethylenenaphthalate (PEN) for the substrate. The threshold voltage was controlled by the chemical doping with F_4TCNQ (tetrafluorotetracyano-p-quinodimethane) [4]. Then, the matching between input and output voltages, which is important for logic circuits to transfer the output to the input of the next stage, was obtained in the inverter characteristics. We have also demonstrated basic logic gates (NOR and NAND), reset-set flip-flops (RS-FFs), and delay flip-flops (D-FFs). Figure 4 shows the master-slave D-FF consisting of 8 NAND and 2 NOT gates. The circuit consists of two gated D latches connected in series, where the slave latch changes the state in response to a change in the state of the master latch. The input-output characteristics show that the master-slave D-FF is triggered on the rising edge of the CLK signal. The master-slave D-FF is the first sequential logic circuit based on carbon nanotube-based transistors.

A 21-stage ring oscillators (44 TFTs) were fabricated to evaluate the operation speed of the present TFTs. The oscillation frequency reaches 2.0 kHz at V_{DD} of -4 V. The delay time of each inverter, $1/2Nf$, where N and f are the number of stages and the oscillation frequency, respectively, is 12 μs/gate. This value is significantly better than the recent studies. Since the delay time is dominated by the parasitic capacitances of overlap regions of the source-gate and drain-gate electrodes, there is a room to improve the operation speed.

3. Fabrication of carbon nanotube TFTs by high-throughput flexographic printing process

Printing process is also attractive to fabricate devices on a plastic film at low cost. We have introduced high-throughput flexographic printing technique in the fabrication process of nanotube TFTs. The flexographic printing method is a kind of typographic printing methods with photosensitive polymer plate. Back-gate-type TFTs has been fabricated on a PEN film. First, a carbon nanotube thin film was transferred from a membrane filter onto the PEN film as previous work. Then, the source and drain electrodes were formed by printing Ag-nanoparticle ink by flexographic printing technique. The throughput of the printing process is 6.6 cm/s. A carbon-nanotube back-gate electrode was transferred on the back surface of the PEN substrate. The fabricated device shows the mobility of 51.5 cm^2/Vs (parallel plate model).

4. Summary

Recent progress of carbon nanotube-based plastic electronics were described. The high-mobility TFTs and the functional logic ICs were fabricated on a plastic film, based on the gas-phase filtration and transfer process. The high-throughput flexographic printing process to fabricate TFT arrays was also introduced.

Acknowledgements

This work is collaborative research with E. I. Kauppinen and co-workers of Aalto University, Finland. This work was partially supported by '08 NEDO Grant, R&D promotion scheme funding international joint research promoted by NICT, ALCA-JST, Grant-in-Aid of MEXT, and the Aalto University MIDE program via the CNB-E project.

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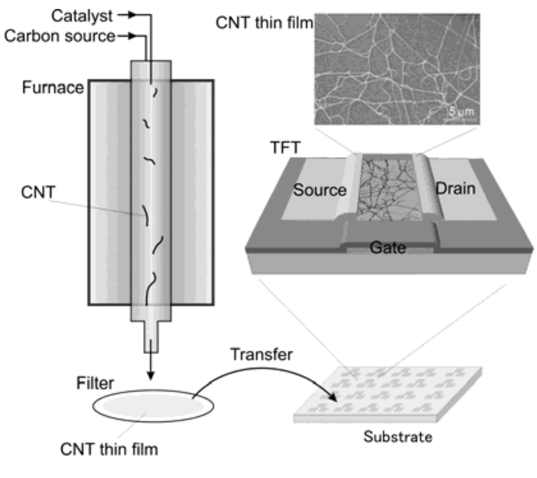

Fig 1. Schematic diagram of carbon nanotube growth, collection by filter, transfer onto substrate with TFT electrodes.

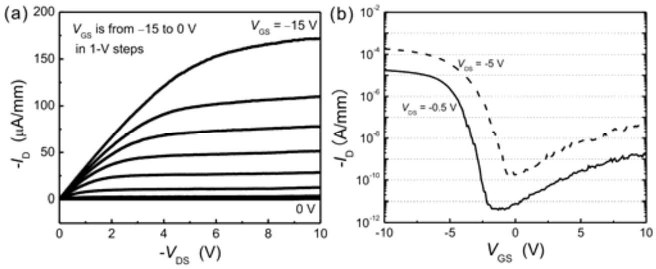

Fig 2. (a) I_D-V_{DS} characteristics and (b) I_D-V_{GS} characteristics.

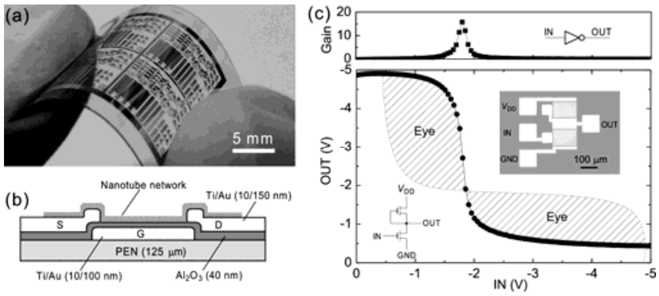

Fig. 3. (a) Photograph of ICs fabricated on plastic substrate, (b) Schematic TFT structure, (c) characteristics of an inverter. The load of the inverter is a gate-source-shorted carbon nanotube TFT.

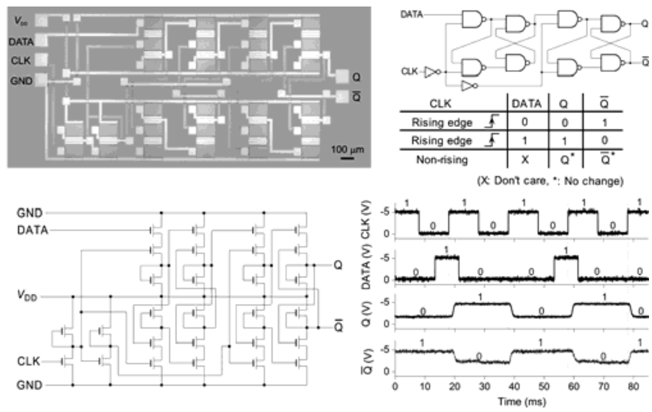

Fig. 4 Carbon nanotube D-FF fabricated on plastic substrate.

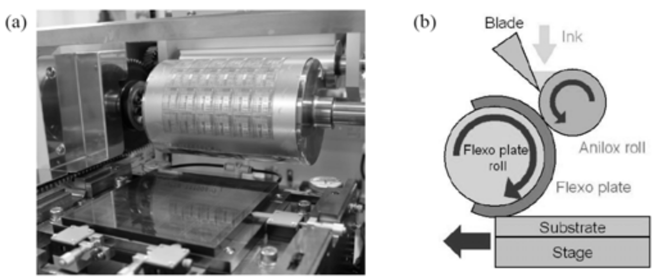

Fig. 5 (a) Photograph of prototype flexographic printer and (b) schematic of flexographic printing process.