Organic Anti-ambipolar Transistor for Flexible Multivalued Logic Circuit

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ABSTRACT

We develop an organic ternary inverter based on a pn-heterojunction transistor on a flexible substrate. The inverters showed well-balanced ternary logic states with high voltage gain. The devices exhibited stable operation even after 100 bending cycles, demonstrating a high potential for combining mechanical flexibility and high data processability.

1 Introduction

Flexible, stretchable and light-weight electronic devices have received intensive attention due to their potential applications in Internet-of-Things (IoT) and wearable electronics. For example, wearable ultrathin ICs can be used in the form of seals as identification tags and in health care applications to monitor essential body parameters. Organic semiconductors play key roles in such advanced electronic applications not only due to their superior electrical and optical properties but also because of their intrinsic mechanical flexibility, enabling us the development of circuitry practically on any kind of common commodities such as papers, plastics and fabrics. However, a bottleneck of the organic electronics should be noted, i.e., low data processability. This is because modern lithographic technologies cannot be applied to organic semiconductors. Multivalued logic circuits (MVLs) predominate in this regard, because MVLs can exhibit three or more number of logical states and thus, can handle higher information compared to the conventional binary logic circuits. Additionally, MVLs can minimize the chip area by reducing the number of constituent elements and promote the development of densely integrated circuits. In this study, we have tackled this challenging issue by developing organic MVLs (OMVLs). The OMVLs can be a game changer for next generation IoT electronics as they can achieve both high integration density and mechanical flexibility together with the advantage of easy patterning processes and low production cost.

2 Experiment

The key componet to realize the OMVLs is an anti-ambipolar transistor (AAT) [1]. Device configuration and molecular structures are shown in the inset of Fig. 1. Uniqueness of the device configuration can be ascribed to a partially overlapped pn-heterojuntion at the center of a transistor channel. Typical semiconductors are α-sexithiophene (α-6T) and a perylene derivative (PTCDI-C8) as p- and n-type, respectively. The devices, consisted of the semiconducting layers, dielectric gate insulators and source-drain electrodes (Cr/Au), were produced on flexible polyethylene naphthalate (PEN) substrates by spin-coating and vacuum deposition processes. All electrical measurements were carried out in ambient condition at room temperature.

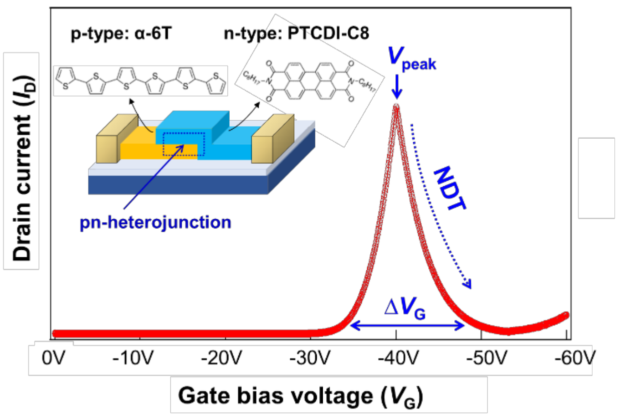

Figure 1: (Inset) Molecular structures of p- and n-type organic semiconductors, device geometry with pn-heterojunction at the channel center, and Λ-shaped transfer curve (red line). The NDT can be observed above peak voltage (V_{peak}).

3 Results and Discussion

A typical characteristic of the AAT is shown in Fig. 1. Here, the drain current (I_D) can pass through only in a specific gate voltage range (ΔV_G). As a result, the I_D shows a steep reduction above a critical voltage (V_{peak}), even though the gate bias (V_G) increases to yield a Λ-shaped transfer curve (red curve in Fig. 1). The reduction in the I_D with increasing V_G can be regarded as a negative differential transconductance (NDT), which can be applied to multivalued logic circuits.

This study is consisted of four parts. The first part focuses on the fundamental operation mechanism of the AAT [2,3]. In particular, the origin of the NDT is discussed. The electrical current flows between the drain-source electrodes only when both p- and n-channels are ON-states. This is the reason of the Λ-shaped transfer curve in the range of ΔV_G and NDT above V_{peak}.

In the second part, the AAT-based ternary inverter is demonstrated as a model device of OMVL [4]. The OMVL is produced by connecting the AAT and n-type transistor in series as illustrated in the left part of Fig. 2. Here, the input voltage (V_{IN}) is provided from the bottom gate electrode, and the output voltage (V_{OUT}) is monitored as a function of V_{IN} at the center electrode. A voltage transfer curve (V_{IN}-V_{OUT} curve) exhibites ternary logic states, denotet as 1, 1/2 and 0, according to the balance of the drain current in the AAT and n-channel as shown the right side of Fig. 2. In addition to these fundamental analysis, the optimizations of consisting materials and device geometries are also discussed to realize low-voltage and full-swing operation.

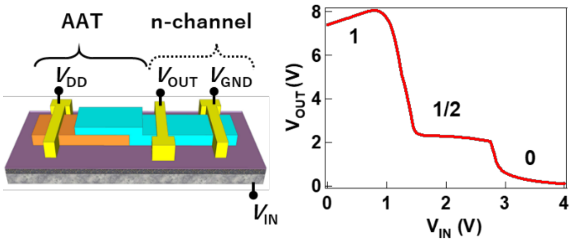

Figure 2: Device geometry of ternary inverter consisted of AAT and n-type channel (left), and (b) voltage transfer curve showing ternary logic states (1, ½, 0) (right) Copyright © 2018, American Chemical Society

The third and fourth parts are related to the advanced applications of MVLs those are optically controllable MVLs [5] and MVLs on flexible substrates [6]. As shown in Fig. 3, the logic states can be precisely tuned upon light irradiation depending on the wavelength. Here, UV or visible light was illuminated on the device from a Xe lamp through respective filters. These results were achieved by the light-induced shift in the threshold voltage in the AAT and n-channel. That is, minority carriers generated by light accumurated at the electrode/channel interface to affact on the threshold voltage. Then, distinct photoresponces of p- and n-type organic semiconductors are responsible to the wavelength dependence, making it possible the various optical controllability.

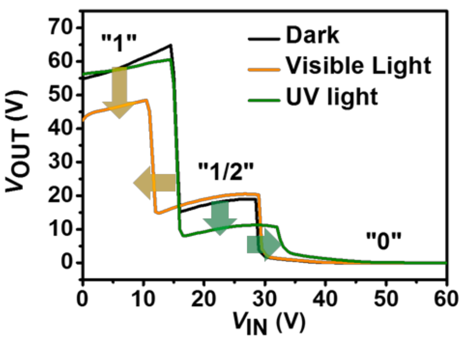

Figure 3: Optical controllability of ternary logic states (1, ½, 0) by UV/visible light irradiation. Visible light affected mainly on the logic state 1, while the logic state 1/2 was tuned by UV light.

Figure 4 demonstrates the MVLs formed on a plastic substrate (left), where the devices showed stable operation even after the 100-times repeated bending test (right). Here, key materials the dielectric gate insulator: PMMA or HfO_2. Each material has respective advantages; the polymeric PMMA showed advanced bendability and high-k HfO_2 enabled low-voltage operation.

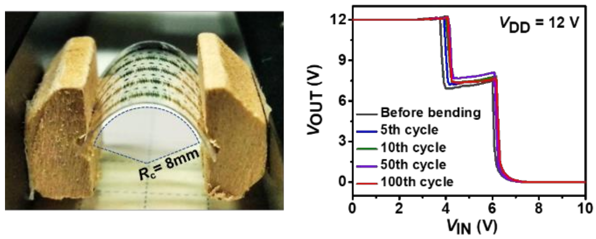

Figure 4: Photograph of ternary inverter fabricated on a plastic substrate (left), showing distinct ternary states even after the100-times bending test (right). Copyright 2021 The Japan Society of Applied Physics

4 Conclusions

We developed the flexible MVL, in which the NDT yielded in the anti-ambipolar transistor played a key role. This device has high potential to attain the mechanical flexibility and data processing capability at the same time to overcome the long-standing challenge of the organic electronic.

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