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300-nm High Gain Multi-Stage Organic CMOS Inverters

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Abstract

Ultra-thin and ultra-flexible electronics can enable skin-level integration of electronics for accurate monitor of biological signals. We have created sub-300-nm thin multistage organic CMOS inverters capable of such applications. Operating at 5 volts, 1-stage, 2-stage, 3-stage, 4-stage, and 5-stage inverters resulted in maximum gains of 30, 49, 67, 77, and 79 dB. The mechanical flexibility was demonstrated by laminating the inverter on a pre-stretched elastomer, which was subsequently repeatedly stretched.

1. Introduction

The goal of creating an artificial skin capable of monitoring medical conditions, for instance with electrodes placed directly on patient's skin or on the heart, requires ultra-thin, flexible, stretchable, and bio-compatible electronics [1]. Furthermore, the biological signals are relatively weak and require significant electrical amplification [2]. The use of rigid and inflexible inorganic electronics presents a challenge for soft, oddly shaped, and very porous human bodies and organs, as these electronics have to be embedded in organic materials before implantation [2]. Organic electronics promises to fulfil all of these requirements without the need of additional encapsulation, resulting in much thinner devices. We have in the past demonstrated electronic devices with a total device thickness of about 2 µm [3]. The bending thickness, and subsequently the conformity, of a thin film is proportional to its thickness cubed [4]. Decreasing the total thickness below the 2 µm mark, would therefore significantly reduce the bending stiffness making the devices much more conformal and adhesive to the organs surface roughness, allowing for more accurate monitoring of biological signals. Amplifying a signal closer to the source typically leads to a higher signal-to-noise ratio. This necessitates the circuit level integration, namely ultra-thin-film amplifiers, to be deployed, for instance, on patient's skin or their brain [2].

Having previously demonstrated a record-thin, low voltage organic field effect transistor that, including the substrate and the encapsulation layers, is less than 300 nm thin [5], in here we report on fabricating record-thin, low voltage, ultra-flexible CMOS inverters based on the same sub-300 nm fabrication technology. When cascaded, these record-thin inverters can exhibit ultra-high gains in excess of 79 dB.

2. Results

The device structure, shown in the inset of Fig. 2(a), is parylene (60 nm)/Au (30 nm)/parylene (60 nm)/ dinaphtho[2,3-b:2',3'-f]thieno[3,2-b]thiophene (DNTT) or N,N'-bis(n-octyl)-dicyanoperyl-ene-3,4:9,10-bis(dicarboximide) (PDI-8CN2) (30 nm)/Au (30 nm)/parylene (60 nm), for a total thickness of approximately 270 nm. The fabrication process includes thermally evaporated gold source, drain, and gate electrodes, as well as the organic semiconductors, DNTT or PDI-8CN2 [5, 6]. CVD-deposited biocompatible parylene serves as the top (substrate) and bottom encapsulation layers. The V_{IN} and V_{OUT} via holes are obtained with a desktop laser cutter. The devices are fabricated on glass substrate, covered with a thin layer of fluorinated polymer, and are subsequently delaminated. The delamination step includes removing a sacrificial layer of PVA by dissolving it in deionized H_2O.

The device characteristics of a fabricated CMOS inverter are listed next (the circuit diagram is shown in the inset of Fig. 2(b)). The channel length for both types of transistors was 30 µm, with channel widths of 800 µm and 2400 µm for p- and n-types devices, respectively. The individual devices, with 5 V operating voltage, were post-fabrication (pre-bend) and post-delamination (post-bend) electrically characterized, with average recorded mobilities of 0.45 and 0.31 cm^2/Vs for p-type devices, and 0.014 and 0.011 cm^2/Vs for n-type devices, respectively. The ON/OFF ratios of pre- and post-bend devices were $\sim 10^5$ and $\sim 10^5$ for p-type and $\sim 10^3$ and $\sim 10^1$ for n-type OFETs. The threshold voltage has been shifted from -0.41 V to -1.06 V for p-OFETs, and from -0.52 V to -1.84 V for n-OFETs. The yield, calculated on 20 p-type and 20 n-type devices, was recorded as 100% and 95%, respectively.

To demonstrate the extreme bending and conformability of these ultrathin devices, we have placed the film on a 50% pre-stretched elastomer, which was subsequently allowed to relax. This resulted in multiple highly irregular ridges for the film to adhere to. The elastomer was subsequently stretched 100 times, up to the original 50% pre-stretched limits. The film was observed to confirm and adhere very well to the elastomer, with the bending radius previously reported as being less than 1.5 µm [5].

Following the bending test, we have performed the electrical characterization of this 1-stage inverter. Fig. 1 portrays the family of transfer curves. The maximum calculated gains, obtained for V_{DD} of 5, 4, 3, and 2 volts, were 20, 18, 15, and 9 dB.

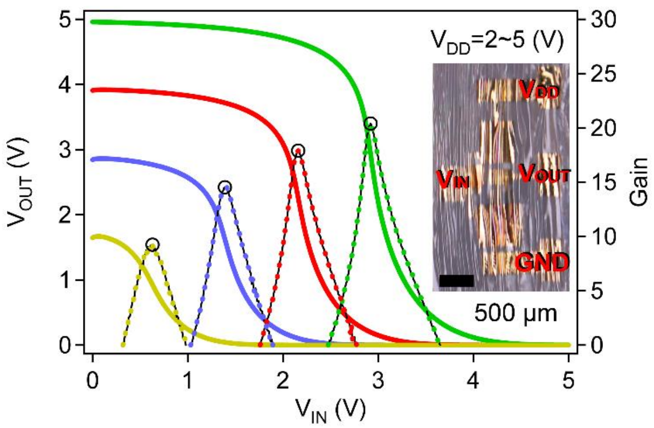

Fig. 1. Transfer function and gain of a 1-stage CMOS inverter, measured for V_{DD} of 5, 4, 3, and 2 volts. The inset shows a picture of a crumpled circuit on a relaxed elastomer.

Biological signals are often relatively weak and require significant electrical amplification. We have fabricated sub-300 nm thin organic electronic multi-stage inverters, which are simple electrical circuits that can be operated around the switching voltage to obtain high gain circuits. Fig. 2(a-c) demonstrate transfer curves of 1-, 2-, and 3-stage CMOS inverters, measured for V_{DD} of 5 volts. The calculated gains were recorded as 30, 49, 67, 77, and 79 dB for 1-stage, 2-stage, 3-stage, 4-stage, and 5-stage inverters, respectively.

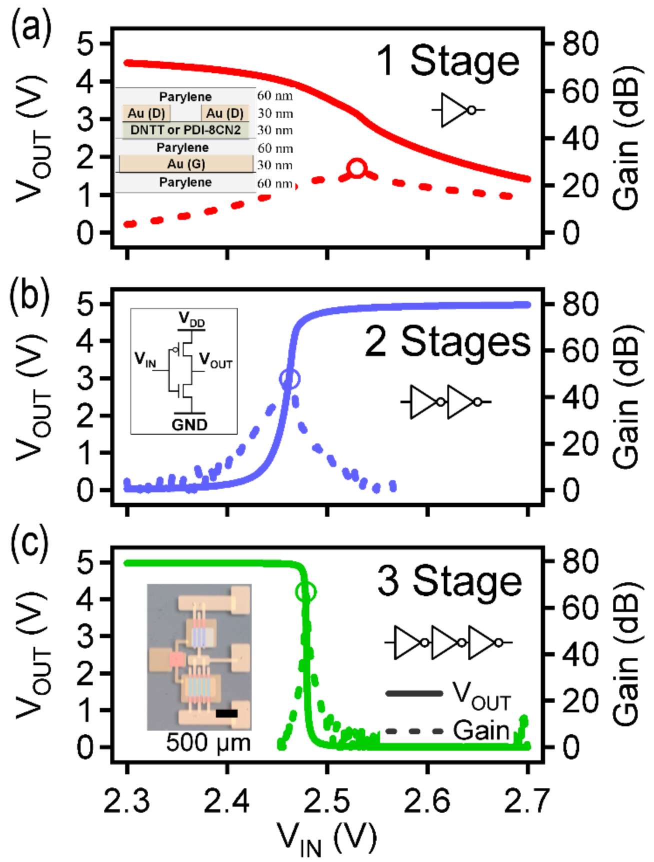

Fig. 2. Transfer curves and gains of cascaded multistage inverters, showing increasing steepness (higher gain) with increased number of stages. (a) 1-stage inverter with maximum gain of 26 dB. The inset shows the architecture of individual transistors, with thickness layers of individual materials. (b) 2-stage inverter with a maximum gain of 48 dB. The inset indicates a diagram of the inverter circuit. (c) 3-stage inverter with a maximum gain of 67 dB. The inset shows a picture of a 1-stage CMOS inverter.

3. Conclusions

We have fabricated a record thin, sub-300 nm organic CMOS inverters. We demonstrated physical flexibility of these devices by laminating them on a pre-stretched elastomer that was subsequently stretched 100 times, akin to the medical electronics being placed on human skin. The electrical characterization of multistage inverters was conducted with the operating voltage of 5 volts. The recorded gains were 30, 49, 67, 77, and 79 dB for 1-, 2-, 3-, 4-, and 5-stage inverters, respectively.

We believe that this demonstration represents a significant step towards realizing complex skin-level and possibly even implantable electronics.

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