J-3-03

Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp565-566

On the reset operation of organic cross-coupled inverter

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***Abstract*—We discuss the design and operation of a circuit called cross-coupled inverter (CCI). Experimental measurements combined with circuit simulations reveal that the most compact circuit structure of CCI cannot carry out proper reset operation when designed using organic transistors. Through the comparison with the operation of silicon counterpart, a possible remedy is proposed, and the robust reset operation is verified.**

1. Background

Organic transistors bring several distinct advantages over conventional silicon transistors; the organic circuits can be fabricated inexpensively on flexible materials through printing processes. Owing to their cost efficiency, identification of the objects on which the organic transistors are printed, is one of the novel and promising area of applications [1]. Hence, the design of physically unclonable function (PUF) [2,3], which serves as a unique fingerprint of the circuit or the object the circuit is printed on, using organic transistors is gaining increasing attention.

In this work, we analyze the design of coupled inverter circuits using organic transistors, which is an important primitive to construct particular types of PUF circuits.

2. Cross coupled inverter and its operation

The schematic of a cross-coupled inverter (CCI) is shown in Fig. 1(a). Fig. 1(b) shows a microphotograph of organic CCI corresponding to the schematic. The CCI is a fundamental component of various PUF circuits, such as SRAM PUF [4] or buskeeper PUF [3]. An internal state of the CCI, which is stored as the logical high and low voltages at the internal node pair, `Vlin` and `Vrin`, are isolated from the output nodes `Vlout` and `Vrout` by access inverters.

The CCI circuit starts its operation when given a supply voltage, typically at the bootup time of the circuit. Requiring no input signal, the logic states of the internal nodes are determined through the coupled feedback of the inverters. Even though the circuit is identically designed and fabricated, different circuit instances output random and different values according to the relative strengths of the inverters. As the output of the circuit is determined during fabrication process, it is unpredictable even by the manufacturer of the circuit.

As illustrated in Fig. 2, the state of CCI is reset when the supply voltages are equalized. The voltage application after either of the two resets, vdd- or vss-reset, comes the evaluation to obtain the output of the circuit. Fig. 3 illustrates the waveforms at nodes `Vlout` and `Vrout` measured using a parametric analyzer as an oscilloscope. Contrary to our expectation which is illustrated in Fig. 4, the reset of the nodes is incomplete, giving incorrect outputs in the following evaluations. Even worse, the state obtained in “eval-2” depends strongly on the result of the proceeding evaluation.

The operation of organic CCI circuit is compared with that of silicon CCI to investigate the cause of the malfunction. As seen in Fig. 5(a), in the case of Si circuit, the internal node voltages are completely equalized by the drain current of the MOSFETs followed by the backgate current. Meanwhile, in the case of organic transistor, once the drain current stops flowing due to the reset operation, DC bias is not removed because transistors turn into cut-off region and no backgate terminal is available.

3. Organic CCI with passgate reset

To ensure robust operation, we propose to use a passgate switch that connects the internal nodes of CCI, as shown in Figs. 6(a) and 7(a). Instead of equalizing supply voltages, the passgate switch now forces to reset CCI. Though two control signals, `Vgp` and `Vgn`, are newly required for resetting the circuit operation becomes more reliable than before.

Before performing the measurement of the proposed CCI, the operation of an organic passgate switch in Fig. 6(b) is verified. Fig. 8(a) shows the measured transfer characteristic of the passgate switch. During the evaluation period in which switch is closed, two terminals `Vin` and `Vout` are connected and their voltage difference is zero, while in the reset period, the two terminals become open. Fig. 8(b) shows the operation of the proposed CCI in Fig. 7(b). During the reset period, the two output nodes are equalized without DC offset. The operation in evaluation period after reset works correctly.

4. Conclusion

In this work, we proposed a structure of CCI with passgate switch as an important PUF primitive using organic transistors. Through the measurement of the organic CCI and the comparative simulation with Si CCI, the cause of malfunction in the reset operation is clarified, and the correct operation of the proposed circuit is also confirmed.

Acknowledgment This work was partially supported by JSPS KAKENHI Grant 17H01713. The authors also acknowledge support from VDEC, the University of Tokyo in collaboration with Synopsys, Inc.

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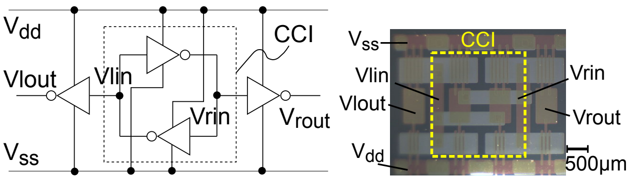


(a) Circuit schematic (b) Microphotograph

Fig. 1: Circuit schematic and the layout of cross-coupled inverter (CCI) using an organic transistor process.

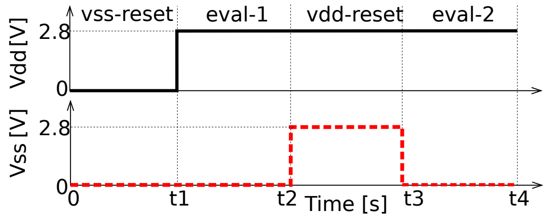
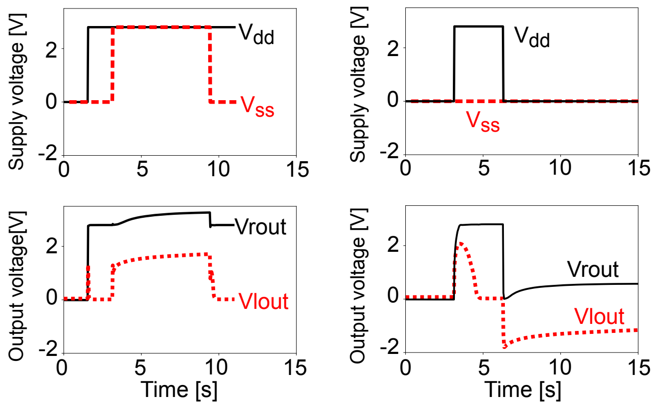


Fig. 2: Reset and evaluation operations of the CCI. Preceeding to the evaluation, the internal state of the CCI is being reset at the voltage of Vdd (2.8 V) or Vss (0 V).



(a) Vdd-reset (b) Vss-reset

Fig. 3: Measured output of CCI circuit in Fig. 1 during and after reset. DC offset exists between the internal nodes in the reset period, affecting to the result of the subsequent evaluation.

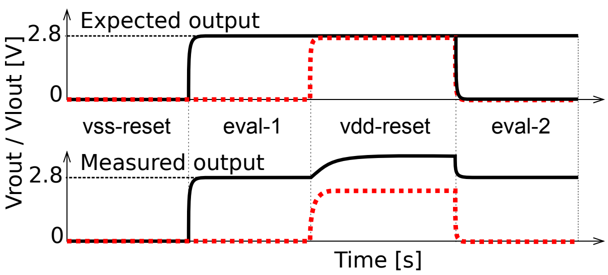
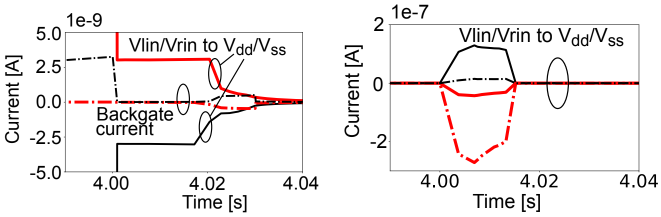


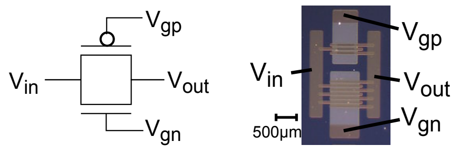
Fig. 4: Illustration of the excepted and measured output voltages of the CCI.



(a) Si: large MOSFET current flows until about 4.02 s, and then backgate current starts to flow to make the internal node voltages equal.

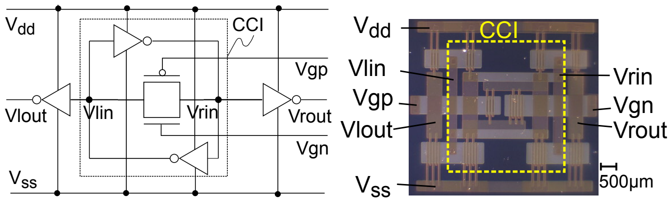
(b) Organic: transistor current flows from 4 s to 4.02 s, and then no current flows thereafter. With the absense of backgate, the voltage of internal nodes stayes unequal.

Fig. 5: Simulated transistor currents in CCI. The reset signal is given at 4.0 s. We used a level3 model [5] and a dedicated model based on [6] for the simulations of silicon and organic transistors, respectively.



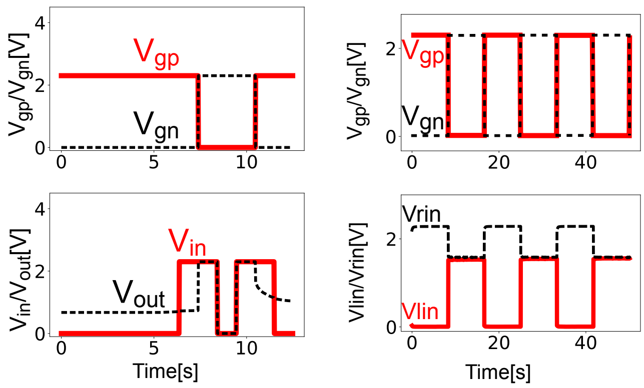
(a) Circuit schematic (b) Microphotograph

Fig. 6: An organic passgate switch used in the proposed CCI. The layout pattern of the passgate switch is designed on the same chip with the CCI but placed separately for independent characterization.



(a) Circuit schematic (b) Microphotograph

Fig. 7: The proposed CCI with a reset passgate switch fabricated using the same process with Fig. 1(b).



(a) Measured waveforms of an organic passgate switch (b) Measured operation of the proposed CCI with passgate switch

Fig. 8: The measured waveforms of the operation of a passgate switch (Fig. 6) and the CCI with passgate reset (Fig. 7).