Organic Electronics 51 (2017) 137–141

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Organic physically unclonable function on flexible substrate operable at 2 V for IoT/IoE security applications

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A R T I C L E I N F O

Article history:
Received 24 March 2017
Received in revised form
12 August 2017
Accepted 18 August 2017
Available online 19 August 2017

Keywords:
Organic transistor
Self-assembly
Low voltage
Flexible
Security
Physically unclonable function

A B S T R A C T

We fabricated organic ring oscillators (ROs) on a flexible substrate and utilized them as the core circuit of a physically unclonable function (PUF). An RO-PUF is a security primitive that generates unique identification numbers (IDs) by extracting the frequency variation of the RO. We fabricated two RO-PUFs and evaluated their IDs in terms of stability and uniqueness at various operating voltages. The experimental results indicate that our RO-PUFs have a high degree of uniqueness and exhibit good stability relative to voltage fluctuations with a nominal operating voltage below 2 V.

1. Introduction

Recently, the Internet of Things/Everything (IoT/IoE) has become a focus of constant attention. In the IoT/IoE, various devices are assembled into one or more networks. A large problem in these systems lies in determining how best to authorize or identify devices that reside at the edges of the network so they can communicate correctly. However, it is difficult to arbitrarily create unique identification numbers for large numbers of devices. To address this problem from a security perspective, physically unclonable functions (PUFs) [1] have been intensively studied [2,3]. A PUF is a type of security device that utilizes the internal variations that arise during the fabrication process. For this reason, it is fundamentally difficult to counterfeit, imitate, or falsify PUF devices. Organic circuits are advantageous for realizing the security of ambient electronics, such as RFID tags, polymer banknotes and wearable electronics due to their flexibility or stretchability when implemented on polymer or thin film substrates. In addition, some types of organic/inorganic materials can be dissolved into organic solvents to create inks with chemical modifications, which are expected to reduce the production cost of printing technology in the future. However, to the best of our knowledge, organic devices, and PUFs in particular, have been rarely studied as security circuits.

In this study, we fabricated organic PUFs on flexible substrates, evaluated their stability in terms of changes in the operating voltage, and estimated their uniqueness for ID generation applications.

2. Experimental

2.1. Fabrication process

We fabricated organic devices using thermal evaporation and solution processes. The transistor structure is shown in Fig. 1(a), and includes the top contact and bottom gate structure. First, we deposited a 25-nm thick aluminum layer onto a 75-μm thick layer of polyimide based film to act as gate electrodes. Subsequently, this aluminum layer was exposed to an oxygen plasma treatment for 30 min to form a 4-nm thick aluminum oxide layer. Then, we immersed the substrate into an isopropyl alcohol solution of n-octadecylphosphonic acid for 2 h. After immersion, we rinsed the substrate with isopropyl alcohol and annealed it at 100 °C for

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http://dx.doi.org/10.1016/j.orgel.2017.08.022

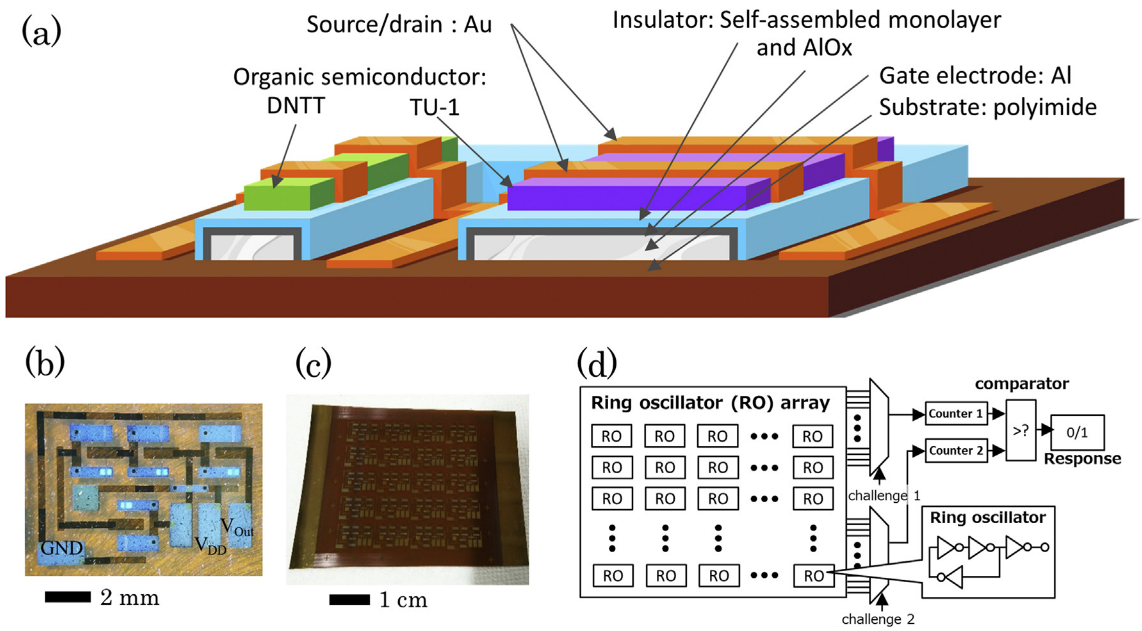

Fig. 1. (a) Schematic structure of the 2-V operable complementary inverter with an organic thin film transistor. (b)(c) Optical image of the organic ring oscillator (b) and the ring oscillator array (c). (d) Schematic diagram of the number generation system.

10 min [4]. The combination of the AlOx and self-assembler functions as the gate dielectrics. We then deposited organic semiconductor DNTT (p-type) [5,6] and TU-1 (n-type) [7,8] onto the gate dielectrics layer by thermal evaporation. Finally, Au was deposited onto the semiconductor to act as the source and drain electrodes, and the circuit traces. The nominal channel length was 10 μm, and the channel widths were 250 μm (for p-type) and 1000 μm (n-type). Using these complementary transistor elements, we fabricated 14 three-stage organic ring oscillators (ROs) (see Fig. 1(b) and (c)).

2.2. Evaluation procedure for the organic RO PUF

The 14 ROs were divided into two groups, and two organic RO PUFs were assembled that each consisted of 7 ROs. A schematic diagram of the RO PUF is shown in Fig. 1(d). The RO PUF receives two inputs (= *challenges*) that target two ROs, then their oscillating frequencies are compared to generate a 1-bit output (= *response*). To estimate the bit error rate, the frequency of an RO is obtained by averaging 1001 times of measurement with a 500-ms interval, which is limited by the measurement system. Therefore, the measurement time becomes 500 s, in total. After the 500 s, the measurement period elapses, 1001 frequency points are obtained for each RO, and eventually 7 × 1001 data points are obtained for each RO PUF.

By comparing the frequency data of the ROs at each measurement time, we generate the responses of the RO PUF. In this case, the number of possible challenges (= the combination among seven ROs) becomes $21 = {}_7C_2$, and thus we obtain a *response matrix* of size 21 × 1001 for each RO PUF (see Fig. S1). The columns of this matrix represent the response to each challenge at each time, and the rows of the matrix show the time evolution of the response for the challenges.

The performance of the PUF is characterized by the intra-PUF Hamming distance (*intra-HD*) among the responses from the same PUF, and *inter-HD* among the responses from different PUFs. The intra-HD represents the stability of the PUF responses, and the ideal value is zero. The intra-HD is calculated by XORing the expected responses and the actual response matrix (see Fig. S2(a)). The expected response is one in which each bit is determined by majority voting over the obtained responses. The inter-HD represents the uniqueness of the PUF responses, and the ideal value is 0.5. The inter-HD is calculated by XORing the response matrices of two (or more) PUFs (see Fig. S2(b)).

2.3. Materials and equipment

A flexible polyimide film (UPILEX-75s, Ube industries, Ltd.) was used for the substrate. For the organic semiconductor materials, Dinaphtho[2,3-b:2′,3′-f]thieno [3,2-*b*]thiophene was purchased from sigma-aldrich. An N-type soluble semiconductor named TU-1 was provided from Ube industries, Ltd. Self-assembled monolayer, n-octadecylphosphonic acid is purchased from PCI synthesis.

For measurement, we utilize the DSO9104A digital oscilloscope (Keysight technologies) and its data-logging software interface named BentchVeu. For the voltage source of RO, the 2400 source meter (Tektronix, Inc.) is also used. All measurements were carried out in atmospheric air and in the dark.

3. Results and discussion

3.1. Organic ring oscillator

Fig. 2(a) shows the oscillation waveform of our organic ring oscillator. This three-stage RO works well with an oscillation frequency of about 1 kHz. The single p-type and n-type organic transistors that were fabricated simultaneously show mobilities of 0.6 and 0.06 cm^2/Vs, respectively. The channel length L is 10 μm, and the channel overlap W_c is also 10 μm. The cut-off frequency of the transistor is proportional to the transconductance g_m, and inversely proportional to the gate capacitance in a unit area C [9]. A ring oscillator consists of inverters connected in series. Therefore, the delay time, which is related to the inverse frequency, becomes the summation of the delays of all inverters. The frequency of the ring oscillator f_{osc} can be calculated as follows.