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High rectifier output voltages with printed organic charge pump circuit

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ABSTRACT

It is known that in many wireless organic electronic applications the required supply voltage is higher than the accessible signal amplitude. Therefore, voltage multiplier circuits are needed in many cases. We report a gravure printed organic charge pump circuit operating at 13.56 MHz suitable for rectified voltage amplification in printed electronic devices. The circuit, consisting of four diodes and four capacitors, has been monolithically printed using only high volume production compatible manufacturing methods. With 10 V AC input the output of the circuit at 13.56 MHz is 8.4 V and 11.8 V using 1 MΩ and 10 MΩ output loads, respectively. At 13.56 MHz the output voltage of the charge pump is three times higher than the output of a half-wave rectifier. The results demonstrate the possibility to print efficient high frequency (HF) charge pump circuits to meet the supply voltage requirements of the printed electronic applications.

1. Introduction

Development of processes for printed electronics offers a novel way to produce more complex electronic components, systems and applications. Much effort has been put, for example, into developing printing processes for organic Radio Frequency IDentification (RFID) that would enable high throughput production of flexible and low cost tags [1–3]. However, high supply voltages are required in most of the state-of-the-art printed logic circuits utilizing thin film transistors with polymeric semiconductors and low-k dielectrics. To overcome the problem of high supply voltages, low throughput processes like spin coating and vacuum evaporation has been introduced by many research groups [4–6]. Nevertheless, in many cases the required DC supply voltage still remains higher than the amplitude of the AC signal obtained from the antenna. Thus, charge pump or other type of voltage multiplier circuits need to be utilized, instead of a simple half-wave rectifier circuit, to provide sufficient supply voltages for printed electronic components.

Charge pump circuits utilizing diodes and capacitors are commonly used to increase the DC supply voltage level in conventional solid state passive RFID tags [7]. Also printed charge pump circuits have been introduced for 13.56 MHz RFID applications using ZnO based inorganic semiconductors [2,3]. However, in this previous work, relatively thick active layers were required to prevent short circuits between the bottom and top electrodes. This reduces the efficiency of the circuits despite the high performance materials. In addition, limited ambient processing stability is expected due to the low work function electrode materials.

Voltage multiplier circuits like double half-wave rectifiers and charge pumps have been introduced also in organic electronics. In 2007, a 13.56 MHz RFID tag utilizing spin-coated pentacene was reported with the transistor based rectifier having charge pump characteristics [6]. However, the efficiency of the rectifier circuit was low. In 2008, a

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double half-wave Schottky diode rectifier was demonstrated based on vacuum evaporated pentacene [8]. The circuit efficiency was high, but due to the nature of the circuit, the theoretical DC output voltage maximum still remained limited by the input signal amplitude. In 2011, an organic one stage charge pump circuit was introduced with polymeric poly(3-hexylthiophene) (P3HT) diodes [9]. The semiconductor was drop casted, the electrode structures were evaporated and external discrete capacitors were used with high capacitance values. The efficiency of the circuit was low and comparable results have been obtained by using only conventional half wave rectifier circuits. Despite the efforts described above, reported results to date show that there is a need for an efficient and stable voltage multiplier circuit for printed organic applications.

Previously, we have demonstrated a monolithically printed charge pump circuit consisting of ink-jet printed capacitors and gravure printed diodes [10]. The performance of the circuit was low due to the incompatible fabrication processes of the different components on the same substrate. Here, we report on a gravure printed organic charge pump circuit, fabricated only with high volume production compatible manufacturing methods. The circuit is a two stage charge pump including four diodes and four capacitors. Both, stage one and stage two output signals were measured and analyzed. We show DC output voltages higher than the input signal amplitude and discuss the effects of the processing steps on the output performance. All manufacturing and analysis steps were performed in ambient environment.

2. Materials and methods

The charge pump circuits were fabricated on a poly(ethylene terephthalate) (PET) film (Melinex ST506, Dupont Teijin Films) with a sheet-fed gravure printing press (Labratester Automatic, Norbert Schläfli Maschinen). A 100 nm copper layer was evaporated onto the PET substrate and patterned using a wet etching process in which the etch resist was printed using rotary screen printing. After etching, the samples were cleaned by rinsing with de-ionized water and 2-propanol. The dielectric poly(methyl metacrylate) (PMMA, Sigma Aldrich, 120000 g/mol) layers for the capacitor structures were gravure printed onto the pre-patterned copper capacitor electrodes (1.5 cm^2). Three layers of PMMA were printed to prevent short circuits in the capacitor structures. Due to the highly volatile solvents (1:1 ethyl acetate and toluene) only room temperature curing before the printing of the next layer was sufficient. After the dielectric, the poly(triarylamine) (PTAA) semiconductor layer was printed onto the copper cathode electrodes and cured for 5 min at 60 °C. The top electrodes for both the diodes and the capacitors were printed during the same process step by using silver flake ink (PM460A, Acheson Industries Ltd.). The silver flake ink was cured at 115 °C first for 5 min followed by an additional curing for 2.5 min. All the fabrication steps were performed in a dust free environment in ambient air. A photo of the printed circuit is presented in Fig. 1a and a circuit diagram in Fig. 1b.

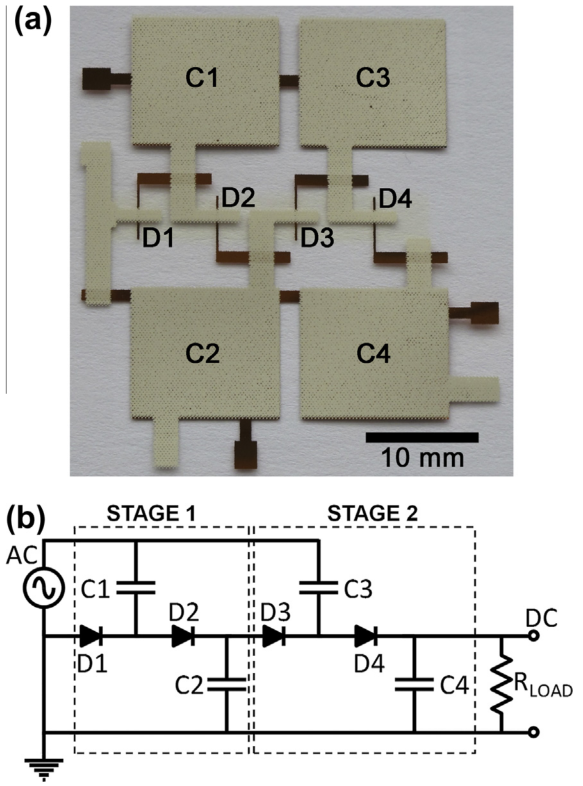

Fig. 1. (a) A photo of the printed 2 stage charge pump circuit. The capacitors (C) and the diodes (D) have been marked for clarity. The printed semiconductor and dielectric layers are almost completely transparent. (b) Circuit diagram of the printed charge pump.

2.1. Characterization of the circuit components

For reliable characterization of the circuit components, the diodes and the capacitors were separated from the circuit. The thickness of the semiconductor layer was calculated based on the diode geometric capacitance at 13.56 MHz (HP Network analyzer 8752A) using relative permittivity of 3 for the PTAA. The capacitance of the capacitors was measured with the same network analyzer. The diode DC current–voltage characteristics were measured using a Keithley 236 source-measure unit. In addition, a Zennium workstation (ZAHNER-Elektrik GmbH & CoKG) was used to measure the capacitance–voltage properties of the diodes at 1 MHz.

2.2. Charge pump output measurements

The output measurements were performed using a 10 $V_{zero\text{-}to\text{-}peak}$ sinusoidal input signal (Keithley 3390). A Tektronix DPO4104 oscilloscope and Tek P6139A 10× voltage probe (10 MΩ) were used to measure the output voltages and the waveforms. The stage 1 and stage 2 outputs were measured over the capacitors C2 and C4, respectively. In addition, the diode half-wave rectification measurements were performed using a discrete filtering capacitor (47 nF) and 1 MΩ load.