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Roll-to-Roll Printable 13.56 MHz Operated RFID Tags on Plastic Foils

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1. Introduction

During the last decade, developing RFID tags using organic semiconductors with a photolithographic process has been demonstrated [1], [2], however, there has been no report of production of tags that had been fully printed and roll-to-roll (R2R) printable. The major reasons for the delay in developing all-printed tags originates from the lack of technology for producing an all-printed plastic rectifier that can provide at least 10 volts DC from 13.56 MHz RFID reader, and an all printed-plastic ring oscillator that can generate 100 Hz of clock signal to read a 96 bit RFID tag in a second under the DC power provided from the rectifier [3]. Here we describe a process that achieves this goal using the working concept of the 1-bit RFID tag as following. First, the printed antenna couples AC power from the transmitted RF frequency of 13.56 MHz from the reader and then the coupled AC power are rectified into at least 10V DC through the printed rectifier. Second, the rectified 10V DC powers the printed ring oscillator and generates clock signals. The generated clock signals are read by an oscilloscope or a real-time spectrum analyzer so that the tag can show “yes” or “no”. A circuit of the fully printed and R2R printable 13.56 MHz operated 1-bit RFID tag that contains the most basic units, such as an antenna, a rectifier and a ring oscillator, is shown in Fig. 1a and printed in three steps: (i) R2R gravure printed antenna, electrodes, gate electrodes and gate dielectrics were formed, (ii) the ring oscillator to generate clock signals under at least 10 V DC was printed, and the rectenna (combined antenna and rectifier) to yield at least 10 V DC at 13.56 MHz was printed. Based on the 1-bit tag, we can further print NAND and OR gates to generate multi bit digital signals.

2. Experiments and Results

2.1 R2R Printed Electrodes and Dielectric Layers

In all this work, two-color units of a R2R gravure printer (Taejin Machinery Co. Korea) (Fig. 1c) were used to print antennas, electrodes, gate electrodes, wires and dielectric layers in a R2R inline process. 13.56 MHz antennas, electrodes, gate electrodes with 200 μm width and wires were first R2R gravure-printed on poly(ethylene terephtalate) (PET) foils (SKC, Korea) of a thickness of 75 μm in the first printing unit using silver gravure inks (PG-007, Paru Co.) with a viscosity of 200 cp and surface tension of 36 mN/m and then passed through the heating chamber

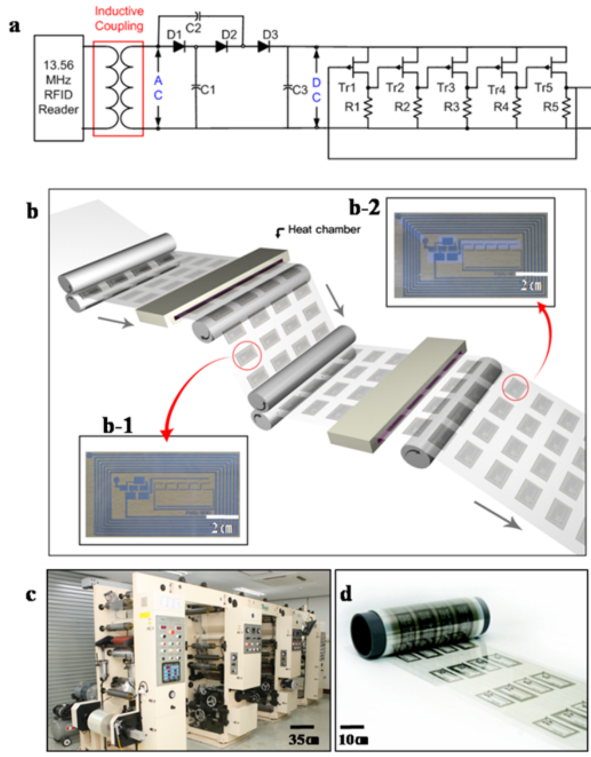

Fig. 1. **a**, Schematic circuit diagram for 1-bit RFID tag. **b-1,** Schematic illustration of R2R gravure-printed antennas, electrodes and wire. **b-2,** The printed dielectric layers on selectively designated spots using high-κ dielectric ink is shown. **c**, The gravure printer used in this work with two-color units. **d**, Roll image of completed R2R gravure printing is used as precursor for printing 13.56 MHz operated 1 to 4-bit RFID tags.

(150°C) for 5 s for curing (Fig. 1b-1). The R2R web speed was maintained at 5 m/min. The printed antennas, electrodes and wires all showed a resistivity of 20 Ω·cm after gravure printing with a printing speed of 5 m/min on PET foils and curing for 10 s at 150°C. The R2R printed antenna with the resistivity of 20 Ω·cm can couple at least 10 V AC from the reader at the given 13.56 MHz.

After passing through the first heating chamber, the printed web was moved into the second printing unit with the same web speed (5 m/min) to print the dielectric layers (Fig. 1b-2) on only designated spots of wires, gate electrodes and bottom electrodes of capacitors using dielectric inks (PD-100, Paru Co.) with a viscosity of 200 cp and surface tension of 30 mN/m. The dielectric constant of the PD-100 was 13. The resulting R2R gravure printed antenna, all electrodes and dielectric layers as shown in Fig. 1d and called as precursors used to print a ring oscillator, a rectifier, NAND and OR gates.

2.2 Single Walled Carbon Nanotube (SWCNT) TFTs and Ring Oscillators

Since the designed circuit has the channel length of 200 μm due to the limit of 20 μm overlay R2R printing registration accuracy, SWCNTs with intrinsic high mobility and stability [6], [7] were considered for the printable active layers. In the process of producing printed SWCNT-ring oscillators, the SWCNT-TFTs are first printed for the resistor-load type inverters. The printed drain-source electrodes with surface resistance of 400~500 Ω/sq could be attained by R2R gravure on R2R printed gate dielectric layer. The active layer, with a width of 4200 μm and channel length of 200 μm, was printed using inkjet with the PR-001 ink provide from PARU Co. Korea. For producing inverters, 50 MΩ resistors to each of the SWCNT-TFTs were printed with patterns of 2.5 mm x 5 mm using carbon paste (Dozen Tech, Korea) and the pad printing method.

All electrical measurements of the printed SWCNT-TFTs, SWCNT-inverters and SWCNT-ring oscillators were carried out under ambient conditions. The mobilities of the printed SWCNT-TFTs could be tuned from 0.03 ~ 5 cm^2/Vs with an on-off ratio of $10^4 \sim 10^2$ by controlling the density of printed PR-001 (SWCNTs) ink. To attain clock signal with a reasonable frequency, SWCNT-TFTs with a mobility of 5.24 cm^2/Vs, a threshold voltage of -4V and a transconductance (g_m) of 0.307 μS were used. Typical SWCNT-inverters with resistor load show stable maximum switching frequencies about 60 Hz with gains of 1.0 using 10 V DC. Based on the SWCNT-TFTs, the generated frequency from the printed SWCNT-ring oscillator was 60 Hz at 10V DC. If we consider some parasitic capacitance on SWCNT-TFTs, the observed frequency of 60 Hz was a reasonable value and the highest value so far demonstrated for fully printed and R2R printable ring oscillators operated at 10 V DC.

2.3 Printed Diodes and Rectenna

To complete a rectenna, the SWCNT-ring oscillator printed tags were used for printing further layers using a pad printer. For constructing the rectifier, a voltage tripler, three Schottky diodes and three capacitors, were fabricated on the SWCNT-ring oscillator printed tags. The reason for using the voltage tripler is that there is low rectification efficiency (ratio of DC output voltage to AC input peak voltage) of each printed diode due to the thick active layers (5 μm), which is needed to prevent a possible short between the bottom and top electrodes. After printing the semiconducting layer on the silver electrode and drying it at 150 °C for 10 s, the top electrode was printed using Al ink. The output electrical characteristics of a printed diode and a printed capacitor at 13.56 MHz are shown about 10 V DC. The printed capacitors all showed capacitance of 1.2 nF/cm^2. After completing the rectifier, the rectified DC voltage of the printed rectenna at 13.56 MHz was measured based on the distance from the 13.56 MHz reader (3ALogics RSK 100). A reading distance of 2 cm has to be kept for attaining at least 10 V DC.

2.4 All printed and R2R printable 1to 4-bit RFID Tags

Based on the provided materials and printing methods for printed SWCNT-ring oscillators and 13.56 MHz rectenna, the circuit for 13.56 MHz operated 1-bit RFID tag (Fig. 1a) was successfully all-printed and R2R printable. The all-printed 1-bit RFID tags were identified using a 13.56 MHz reader and a real-time spectrum analyzer (Tektronix RSA 3303A). As the 1-bit RFID tag approached the reader, about 15 V of 13.56 MHz AC was coupled by the antenna and converted into 15 V DC when passing the rectifier. The converted 15 V DC energized the ring oscillator to generate 102.8 Hz signals that could be read by the real-time spectrum analyzer. Since the supplied DC power from the rectana was 15 V, the observed frequency from the 1 bit RFID tag is higher than 60 Hz of the printed ring oscillator at the power of 10 V DC. Furthermore, 6 NAND and 1 OR gates were further integrated in the 1 bit tag to make 4-bit tag and then, the resulting tag can generate 16 different digital signals as approaching the 4-bit tag to the 13.56 MHz reader.

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