Design and manufacturing of organic RFID circuits

Coping with intrinsic parameter variations in organic devices by circuit design

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Abstract— **A detailed study of device characteristics and parameter variations of organic transistors on foil leads to the conclusion that design of p-type only digital circuits needs to focus on optimal yield, rather than on speed. From this perspective, subsequent generations of organic RFID tags have been realized, by increasing complexity (from 64 bit to 128 bit code generators), by adding functionality (Manchester encoding, anti-collision protocols), and by increasing data rate of the generated ID code (from 752 bits per second towards 50 kbit per second). As such, each of the requirements towards EPC compatible organic RFID tags is shown independently in code generators on foil, but not yet in a single RFID tag.**

Keywords- Pentacene, organic RFID code generators, design for yield

I. INTRODUCTION

Organic semiconductors enable circuit technologies that can be produced at low cost [1]. One of the driving applications for the organic semiconductor technology field is the organic RFID tag [2-4]. Low-cost production processes, such as printing, could lead, amongst others, to the presence of an organic RFID tag printed on any product in the supermarket, providing an easy and quick check-out.

The concept of a 13.56 MHz organic RFID tag [4] is rather straightforward (see Fig. 1). A resonant antenna picks up the electromagnetic field from the reader and the obtained signal is rectified to provide the required DC voltage to empower the code generator block [5]. To obtain sufficient DC voltage from the RF Field, typically a double half wave rectifier is used [6]. Once powered, the code generator block generates a code sequence which drives the load modulator transistor. This load modulator transistor yields antenna current which is sensed again at the reader. Two embodiments of organic RFID tags have been shown, i.e. with the load modulator behind the rectifier [2-4] and in front of the rectifier [4]. The latter yields more modulation depth, but demands excellent characteristics of the load modulator transistor.

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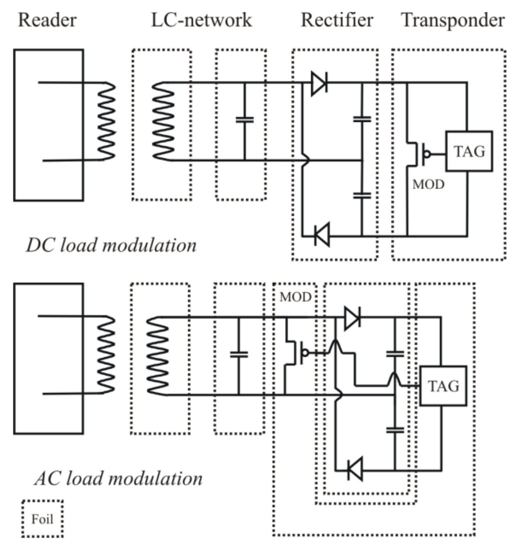

Figure 1. Inductively-coupled organic RFID tags using DC (top) and AC (bottom) load modulation

II. MAIN DESIGN CHALENGE: PARAMETER VARIATION

In most implementations in organic technology, DC load modulation is selected, such that only the rectifying diode has to operate at RF frequencies. Organic layer deposition technologies to obtain organic diodes reaching HF and even UHF frequencies have been elaborated successfully [5,7], and the characteristics of current organic transistors are fulfilling the requirements to be used in the code generators of Fig 1. This brings us to the challenges of designing the code generators in the tags, which we elaborate in this tutorial.

A. Origin of parameter variations

Organic thin film transistors (OTFTs) on foil contrast with classic transistor technologies by an inherently much higher parameter spread, due to the following raisons:

- Patterning/printing technologies for the source-drain contact lead to variations of the effective gate length (L) within each transistor, and hence also current drive variations between the different transistors.
- Dielectric thickness (d) variations are inherent to the deposition techniques used for the gate dielectric.
- Roughness of the semiconductor-gate dielectric interface leads to mobility (μ) variations [8] between the different transistors.
- The random distribution of grain boundaries in crystalline organic semiconductors leads to device to device variations in effective mobility.
- The dimensional stability of the foils during the subsequent process steps [9].

Each of the above-mentioned parameter variations leads to variations in the transistors drive current and threshold voltage (V_T), as can be observed from the approximated transistor current equation in the saturation regime:

$$I_{SD} = \mu \frac{\varepsilon_o \varepsilon_r}{d} \frac{W}{L} \left(V_{GS} - V_T\right)^2 = I_o \left(V_{GS} - V_T\right)^2 . \quad (1)$$

B. Influence on the circuit yield

The spread on the current drive lead to variations circuit speed, whereas the spread in V_T strongly influences yield [10].

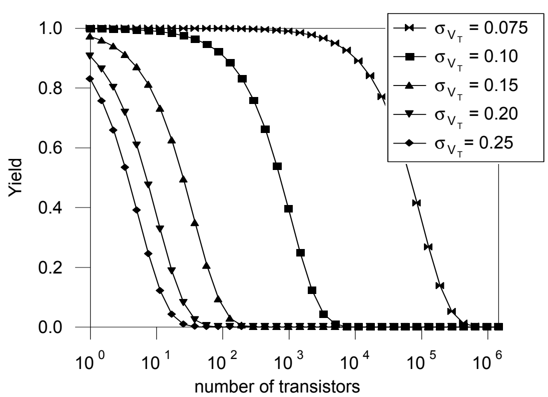

Figure 2. Worst case calculation of the circuit yield as a function of the number of inverters, calculated for V_{DD} = 15V and an average V_T of 3V.

Typically, a profound statistical analysis of both the current drive (I_o) and threshold voltage (V_T) of the transistors is done for each technology before the design of large digital circuits can start. This requires a technology freeze, for at least the period required for the design, which hampers technology progressing along multiple axes.

III. DESIGN EXAMPLES

A. 64 bit organic RFID tag

A first series of code generator designs (8bit, 16bit, 32bit and 64 bit) has been elaborated for being operational from power between 10 V (8 bit code generator) and 14V (64 bit code generator [4]. The schematic of this class of designs is shown in Fig. 3. When the rectifier provides the required DC power, a clock signal is generated by a 19-stage ring oscillator. This clock signal is used to clock the output register, the 3-bit binary counter and the 8-bit line select. This block selects a row of 8 bits in the code. The 8:1 multiplexer, selecting a column of 8 bits in the code matrix. The data bit at the crossing of the active row and column, is transported via an 8:1 multiplexer to the output register, which sends this bit on the rising edge of the clock to the modulation transistor.

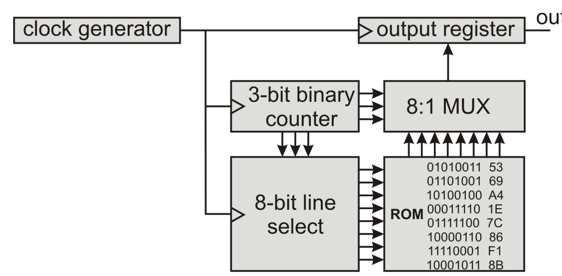

Figure 3. Schematic of the 64 bit organic RFID tag code generator

Fig. 4 shows a photograph of the corresponding foil. It comprises only 414 organic transistors. The inset zooms into a few logic gates. Fig. 5 shows the output that is measured when only the code generator foil is powered with 14 V DC. A data rate of 752 bit per second is obtained. This code generator foil can also be combined with the 3 other foils (resonant antenna and organic rectifier) shown in fig.1. Fig. 6 shows the unamplified signal that is measure back at the reader coil, when being rectified according to the schematic in the inset. The code implemented in the design can be recognized.

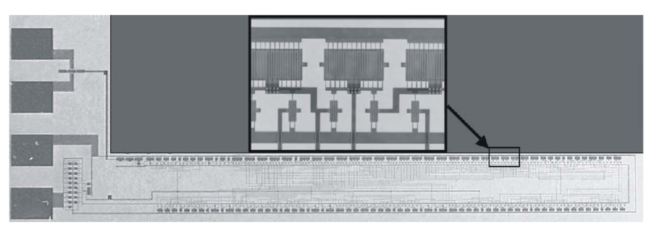

Figure 4. Photograph of the 64 bit organic RFID tag code generator die.

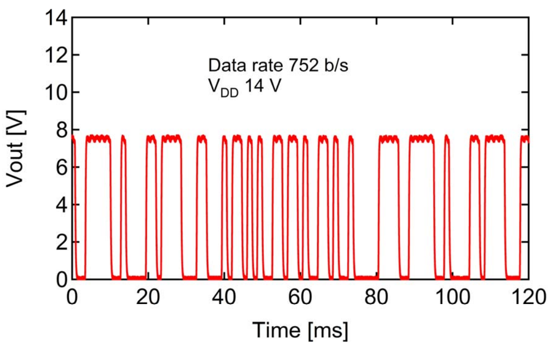

Figure 5. Output of the 64 bit organic RFID tag code generator.

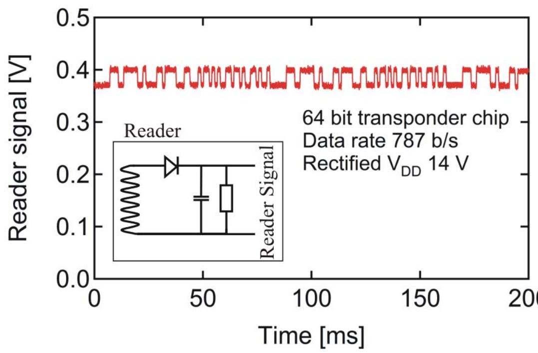

Figure 6. Signal of the organic RFID tag, as has been measure back at the reader coil (unamplified).

B. 128 bit organic RFID tag comprising Manchester encoding and an ALOHA anti-collision protocol

In order to further comply with the EPC specifications, the design has been subsequently extended with an 128 bit code, Manchester encoding at the output and an ALOHA anti-collision protocol [4]. The schematic of the extended design is shown in Fig. 7 and the generated output in Fig. 8. A clear blanking period of about 1 second is observed between the different bursts of the 128 bits of code. The code itself is generated in 83 ms. Fig. 9 reproduces this 83 ms in more detail. The sequence from the schematic in fig.7 can be verified. A data rate of 1529 Hz is obtained and the overall transistor count is 1286 OTFTs.

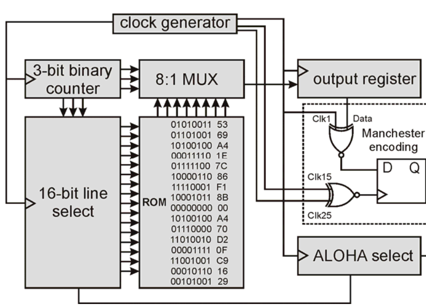

Figure 7. Schematic of the 128 bit code generator comprizing the ALOHA protocol and Manchester encoding.

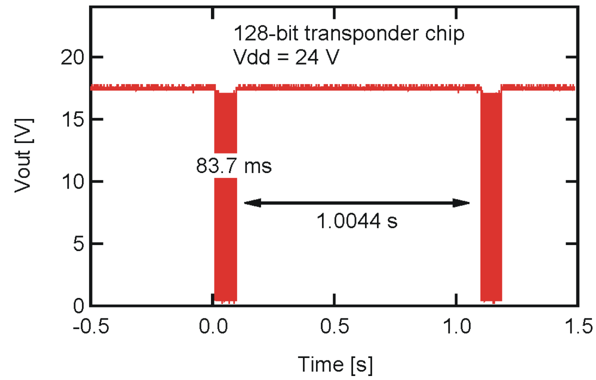

Figure 8. Generated output of the 128 bit code generator.

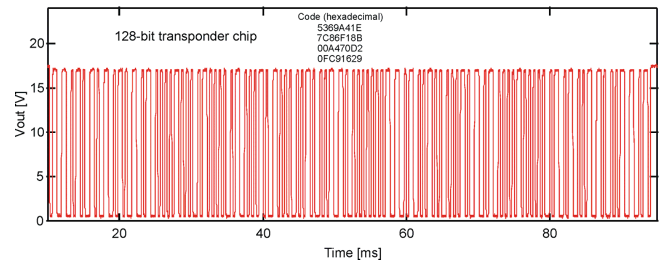

Figure 9. Detail of the code sequence of figure 8.

C. 8 bit code generator at a data rate of 50 KHz

When comparing the specifications of the obtained organic RFID tags (under section A and B) with the specifications for EPC compatible RFID tags, it emerges that the data rate at which the code is generated (752 bit per second to 2 kbit per second) is more than one order of magnitude lower than what is expected for a fluent read-out of the tags in a practical application, being typically 50 kbit per second. However, as the field of organic semiconductors is rapidly evolving, higher mobility materials, improved dielectrics, better patterning techniques, ... become readily available. Designs in this newer technology [11] enable to boost the data rates from 2 kHz to 50 kHz. Fig. 10 shows a photograph of an 8bit code generator on foil that can obtain 50 kHz and Fig. 11 shows the corresponding output sequence.

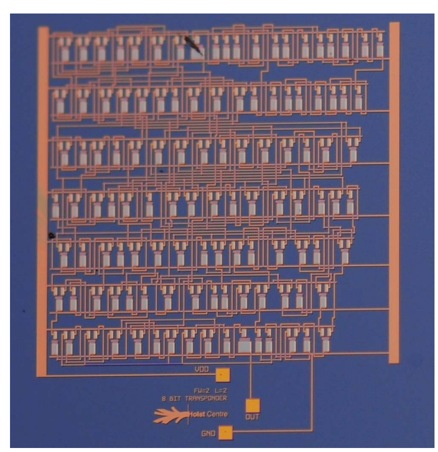

Figure 10. 8 bit code generator operating at a data rate of 50kHz.

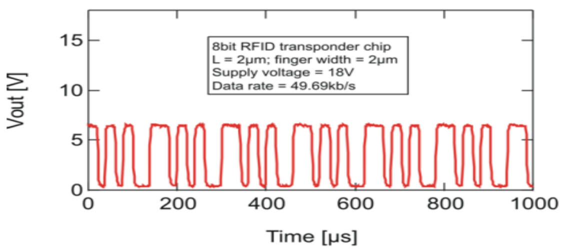

Figure 11. Measument of the output generated by the foil shown in Fig.10.

This 50 kHz data rate can be obtained for an 8 bit code generator, but not yet for an 128 bit code generator with embedded ALOHA anti-collision protocol. This would require a further reduction of the spread in this newer pentacene transistor technology.

IV. CONCLUSION

The state-of-the-art in the field of organic RFID tags is rapidly progressing. All requirements to obtain EPC compatible 13.56 MHz organic RFID tags have been gained, although not yet in the same tag (see table 1). However, all these demonstrations have been obtained using lab scale equipment, whereas parameter variations in industrial large-area, low-cost equipment has inherently much broader parameter variations.

TABLE I. REQUIREMENTS FOR EPC COMPATIBLE TAGS

EPC RFID tag requirement	**Demonstration**
13.56 MHz RF field	Fig. 6
RF Field < 7.5 A/m	Ref. [4]
64-128 bit	Figs. 4-5 (64 bit) Figs. 7-9 (128 bit)
Manchester encoding	Figs. 7-9 (128 bit code generator)
Anti-collision protocol	Figs. 7-9 (128 bit code generator)
50 kbit/sec data rate	Figs. 10-11 (8 bit code generator)

The design strategy that has been elaborated in this paper focuses on p-type only logic for organic circuits. It is clear that currently also n-type organic semiconductors become available. The close integration of n-types and p-types on the same substrate enables organic CMOS technology [12]. The parameter variation that can be allowed in organic CMOS technology is much broader than for current p-type only organic RFID tags [13,14], when two materials can be used of almost equal mobility.

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