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Bendable Printed and Thin-film Electronics for Wireless Communications

F. Ellinger[(1)], K. Ishida[(1)], T. Meister[(1)], B. K. Boroujeni[(1)], M. Barahona[(1)], C. Carta[(1)], N. Münzenrieder[(2,3)], G. Cantarella[(2)], L. Petti[(2)], S. Knobelspies[(2)], G. A. Salvatore[(2)], G. Tröster[(2)], G. C. Schmidt[(4)] and A. C. Hübler[(4)]

(1) Chair for Circuit Design and Network Theory, Technische Universität Dresden, Germany, Frank.Ellinger@tu-dresden.de
(2) Electronics Laboratory, Swiss Federal Institute of Technology Switzerland, Zurich
(3) Sensor Technology Research Center, University of Sussex, Sussex, UK
(4) Institute for Print and Media Technology, Chemnitz University of Technology, Chemnitz 09126, Germany

Abstract

In this paper an overview of the recent progress of bendable ultra-thin and lightweight electronics for wearable wireless communication systems is given. This kind of electronics can be realized on a piece of plastic foil or paper and does not need any standard rigid chips. The focus will be on organic, printed and thin-film electronics and addresses the following components: thin-film transistors (TFTs) with transit frequency (f_t) up to 138 MHz, roll to roll (R2R) printed organic field effect transistors (OFETs) with f_t beyond 50 kHz, an OFET-based R2R printed audio amplifier, active TFT-based wireless transmitters and receivers up to 20 MHz, and R2R printed passive radio frequency identification (RFID) tags in the GHz range.

1. Introduction

The reader is requested to make a small experiment: Please put your smart phone in your front or back trouser pocket and sit down. This is neither enjoyable for you nor your smart phone since it is rigid and not bendable. Now, envision that such kind of communication devices can be fully integrated in a piece of foil, textile or even paper, which is thin, bendable and even stretchable. This would be great, wouldn't it? Another potential application is envisioned in Figure 1 [1]. A future wound tape could transmit the healing status wirelessly to a care person.
Such technologies have the potential for a technical revolution for specific wireless wearable applications, where mechanical flexibility is more important than other parameters such as high data rates.
Rigid semiconductor electronics using silicon [2], silicon germanium [3] or III/V semiconductors [4] providing high frequencies and low power can't be used for such systems. Instead, bendable printed, organic or thin-film technologies can be applied. This is associated with the challenge of low transistor speeds due to the low mobilities of the used flexible semiconductor materials. Circuit architectures have to be optimized taking into account the limited operation frequencies, yields and possible device counts of bendable technologies.
Our paper reviews the status of bendable devices such as passive RFIDs, printed organic and thin-film based transistors, as well as active circuits including amplifiers, fully integrated receivers and transmitters.

Figure 1 Vision of bendable & stretchable radio band-aid

2. Printed RFID

It is today relatively easy to print passive RFIDs since the required printing accuracy is relaxed and simple conducting inks can be used. An overview of tags is given in Table 1. Further info can e.g. be found in [5-9].

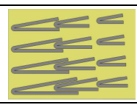
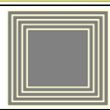
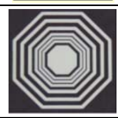
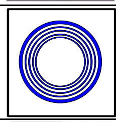
Tag	Structure	Size (mm^2)	Bits
Dipole		17×59	3
Cone		42×30	28
Square		90×30	4
Octagonal		60×60	5
Circular		60×60	3
QR-code with genetic generation		30×30	8

Table 1 Printed chipless RFID in GHz range

3. Mass-Printed Organic Transistors

R2R-printed p-channel OFETs with channel length of 10-20 µm and mobility of 0.2 cm²/Vs were demonstrated. Their structure, current/voltage characteristics and photo are shown in Figure 2. An f_T between 50 and 100 kHz was measured at voltages of around -30 V. This speed is not yet sufficient for radio frequency operation but is already well suited for audio applications. Further info see e.g. [10].

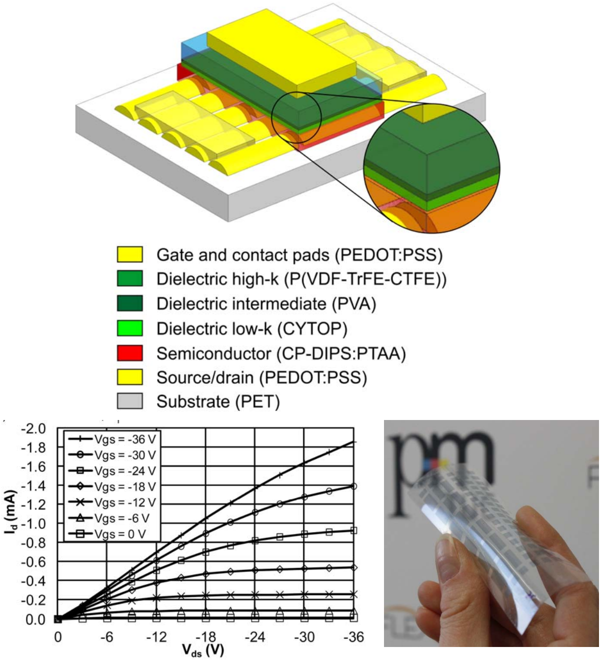


Figure 2 OFET structure, IV-curves and photo

4. Printed OFET Audio Amplifier

Based on the OFET technology outlined in Section 3, an audio amplifier was designed [11]. The circuit is based on 3-stages and has a peak voltage gain of 18 dB at around 1 kHz. Connected with a fully printed speaker it produces a good output volume.

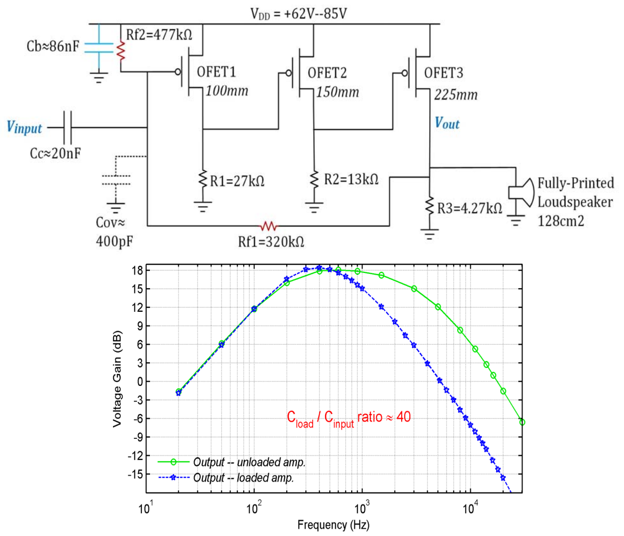


Figure 3 Schematics and measured gain of OFET amplifier

5. Thin-Film Transistor IC Technology

In Figure 4, the structure and the measured f_t of the applied indium gallium zinc oxide (IGZO) TFTs are shown [12]. A polyimide substrate with 50 µm thickness is used. The process offers 3 metal layers for interconnections. At 3 V drain source voltage, an f_t of 138 MHz was measured for the self-aligned TFTs with 0.5 µm gate length. This high speed is maintained even at bending radii down to 3.5 mm. To achieve a good yield and moderate process variations, TFTs with 2 to 5 µm are used for the design of the receiver and transmitter presented in the next sections.

A Rensselaer Polytechnic Institute amorphous TFT model template is applied for the TFT compact modelling in ADS [13]. Moreover, we have developed an improved compact model by including further parameters and equations [14].

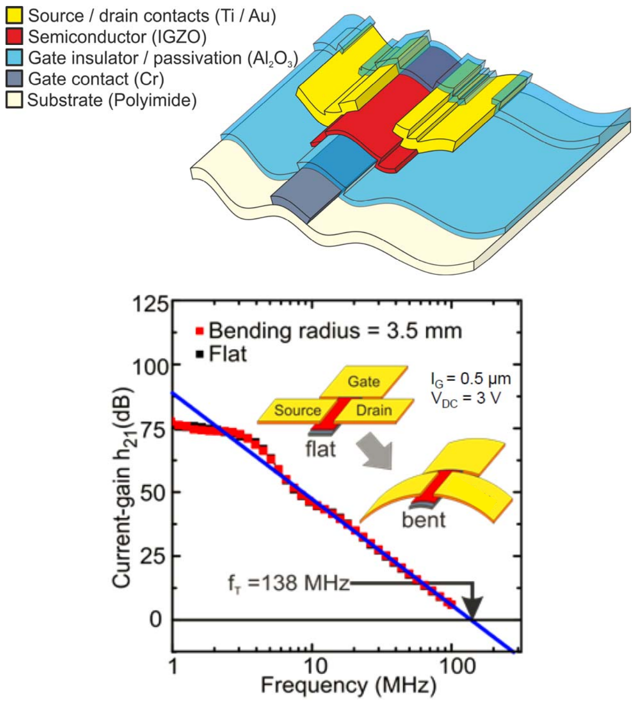


Figure 4 TFT structure and measured transit frequency

6. Wireless TFT Receiver

We have designed a fully integrated IGZO receiver applying amplitude modulation (AM) [15] as shown in Figure 5. The circuit consists of a four-stage cascode amplifier at the RF input, an amplitude detector based on a source follower, and a common source circuit for the baseband amplification. At a carrier frequency ranging from 2 to 20 MHz, a conversion gain of around 15 dB is measured. The 3 dB-bandwidth of the baseband signal ranges from 400 Hz to 10 kHz. This range is comparable to the voice spectrum and also suitable for low-rate wireless data communication. The receiver draws a moderate current of 7.2 mA from a 5 V supply and requires a plastic foil area of 3 × 9 mm².

For this receiver, a tailored textile integrated loop antenna based on woven metal wires was designed [16].

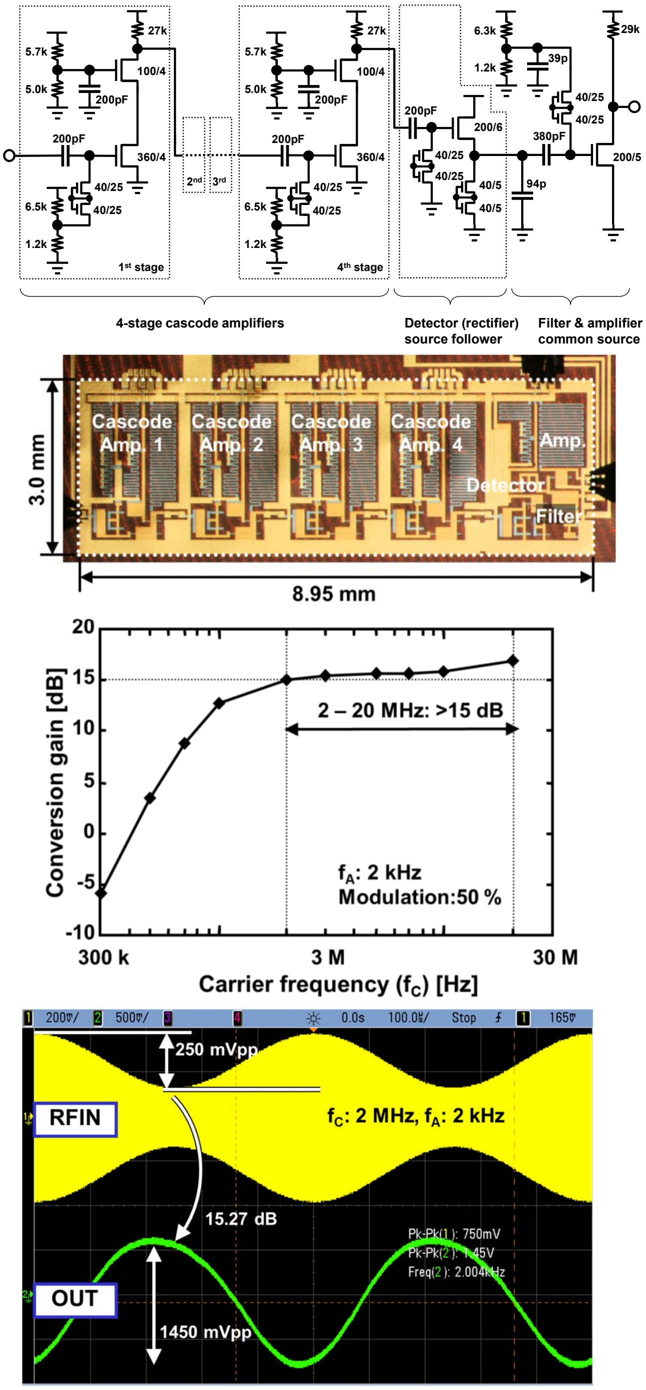


Figure 5 Schematics, photo and measurements of wireless TFT receiver

7. Wireless TFT Transmitter

To enable the realization of a transmitter with a low number of transistors and at relatively high frequency we have chosen the on/off (OOK) keying architecture [17]. The circuit consists of five TFTs with gate length of 2 µm. Figure 6 shows the schematic, a photograph, and the measured wave forms of the OOK modulator. The circuit is characterized with a supply voltage ranging from 3 V to 5 V and an output load capacitance of 15 pF defined by available oscilloscope. Between 3 V and 5 V, the power consumption amounts to 2.2 mW to 6.8 mW. The measured oscillation frequency is 3-3.8 MHz at 3-5 V VDD.

To our knowledge this OOK modulator yields the highest measured oscillation frequency reported to date with a built-in oscillator in flexible IGZO TFT technology. An output swing of around 110 mVpp was measured. A higher swing of 330 mVpp was simulated for a revised version which is currently in fabrication.

It is noted that there are RFID systems in IGZO technology operating at 13.56 MHz. However, they apply an external oscillator clock, e.g. that sent by the reader, see e.g. [18].

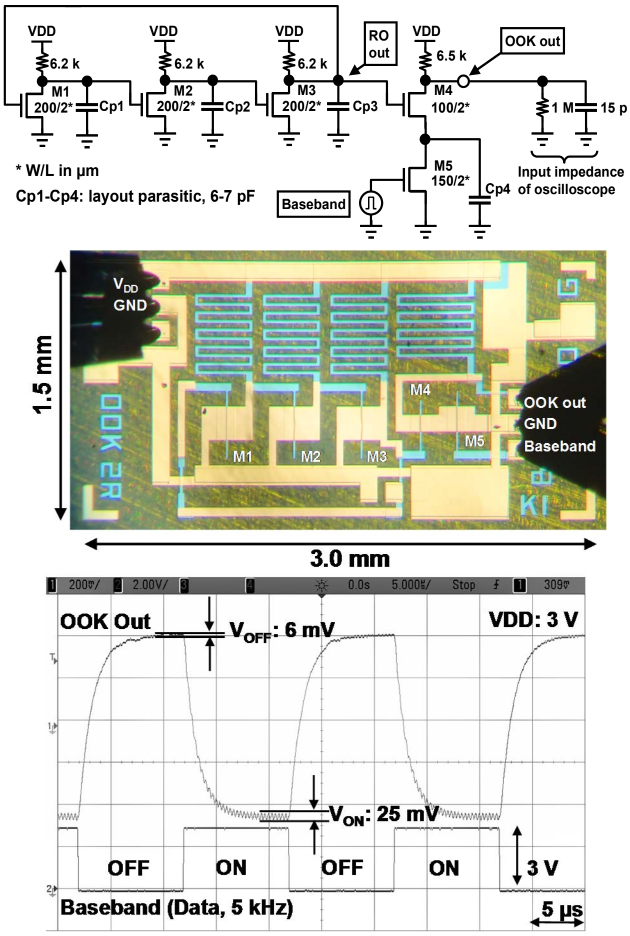


Figure 6 Schematics, photo and measurements of wireless TFT OOK transmitter

8. Conclusions

An overview of the recent progress of bendable ultra-thin and lightweight electronics optimized for wireless communication systems was given. The focus was put on organic, printed and thin-film technologies which can be realized on a simple piece of plastic foil without requiring any standard rigid chips. The following components were discussed: TFTs with f_t up to 138 MHz, R2R printed OFETs with f_t of at least 50 kHz, an R2R printed OFET audio amplifier, low power consuming TFT-based active wireless transmitters and receivers operating up to 20 MHz, and R2R printed passive RFID tags in the GHz range.

Let's go for a revolution by bendable solutions!

9. Acknowledgements

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