3.5mW 1MHz AM Detector and Digitally-Controlled Tuner in a-IGZO TFT for Wireless Communications in a Fully Integrated Flexible System for Audio Bag

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Abstract

We developed a fully flexible AM (amplitude modulation) radio receiver suitable for integration in an “audio bag”, by exploiting the heterogeneous integration of several fully flexible technologies. In this paper, we present a 2.9 mW 2-bit digitally-controlled tuner with a 576 kHz tuning range, a 3.5 mW 1 MHz AM detector and their integration in such a fully-flexible system. Their optimized power consumptions are essential because thin flexible batteries and organic solar cells serve as power supply. The circuits are fabricated in a low-temperature amorphous indium gallium zinc oxide (a-IGZO) technology. For the system integration textile techniques as well as flexible inkjet-printed packages and printed circuit boards (IPCBs) were used.

Introduction

Recently, great attention has been paid to research on flexible and wearable electronics. Many works exist that present circuits in cost-efficient flexible technologies based on organic and metal-oxide thin-film transistors (TFTs). Another branch of research focuses on advanced packaging technologies for flexible and wearable devices [1] around conventional rigid CMOS ICs. Either way, usually some rigid components remain in actual systems.

System Overview: The Audio Bag

The audio bag is a messenger bag augmented with fully-flexible components to enable radio reception of an AM signal and playback of its audio modulating signal. Fig. 1 shows the audio bag and its main modules. The flexible technologies that were combined include a-IGZO TFTs [2, 3], printed organic FETs (OFETs) [4], printed organic LEDs (OLEDs), textile antennas [2, 5], printed piezo-electric speakers [4], flexible rechargeable NiMH-batteries [6], organic photo-voltaic devices (OPVs) [6], button boards, inkjet-printed circuit boards (IPCBs), inkjet-printed passive components, and textile integration. The audio bag demonstrates wireless communication in a fully integrated system with flexible technologies, amongst which the a-IGZO TFTs provide the most prominent electronics functions.

Figs. 2 and 3 show the system architecture and features of the audio bag. The main modules combined in the textile frame are the user interface in the front of the flap, the electronics in the back of the flap, the solar power module [6] in the front of the bag, a piezo-electric printed speaker [4] on each side of the bag, and the textile antenna [2, 5] inside the bag. The control logic, receiver, and baseband amplifier are fabricated in a-IGZO TFT technology [2]. A variant of that technology [3] with a higher breakdown voltage is used to realize the amplifiers driving the speakers. The flexible packaging and integration of the TFT and OFET blocks are done on inkjet-printed circuit boards (IPCBs).

2-Bit Digitally-Controlled Tuner in a-IGZO TFT

The schematic and die photos of the tuner and related channel control logic are shown in Figs. 4 and 6. The tuner is a 2-bit switched capacitor (M1, M2, C1, and C2) that in conjunction with the textile loop antenna selects four different center frequencies. Compared to silicon devices, a-IGZO TFTs present higher leakage, slower switching speeds and larger on-resistance. This results in reactances and resonators of lower quality factors. For this reason, the tuner exploits the high quality factor of the textile loop antenna [5]. To select the center frequency f_0, a 2-bit control word {d1;d2} is provided by four buttons and the a-IGZO TFT channel control logic. The logic sub-blocks are realized in resistor-transistor logic using diode-connected TFTs as load. The supply voltage ranges from 4 V to 6 V. Fig. 5 shows measurements of the channel control logic.

Fig. 7 shows the real part of the measured impedance of the antenna and tuner as seen by the AM detector. The quality factor of the tuner depends on large voltage swings at nodes d1 and d2. In this regard, the output inverters are optimized.

Based on [7] we simulated the center frequencies f_0 for the four possible input words to be {230, 276, 375, 813} kHz. These predict well the measured f_0 = {226, 271, 340, 802} kHz. The measured real parts are roughly 2.5 times smaller than predicted, which is an acceptable accuracy at the f_0 of an LC-tank.

3.5mW 1MHz AM Detector in a-IGZO TFT

Figs. 9 and 12 show the schematic and the die photo of the proposed a-IGZO TFT AM detector. Design and biasing are optimized for the application defined frequency range of 100 kHz to 1 MHz (refer also to the f_0 tuning range above) and a low power consumption, taking the flexible battery and solar driven nature into account. The AM detection is achieved by charging and discharging capacitance C3 via the different impedances of transistors M3 and M4+M5. The frequency range of the detector allows its use with the tuner and large antenna (Fig. 10) in the audio bag and improves over a previously published flexible receiver [2], except in conversion gain. The power consumption (10-fold), area (4.7-fold), transistor count, and complexity are reduced (see Fig. 11). Thus, also an improvement in cost and yield is expected. The measured conversion gain vs. carrier frequency fc and baseband frequency fbb as well as the measured waveform are shown in Fig. 10.

System integration

Fig. 13 shows the integration of the a-IGZO TFT circuit blocks on an IPCB. The substrate material is a 120µm thick PET film. After printing, conductive polyurethane glue and an adhesive film are used to mount TFTs and interposers on the IPCB. Both are cured at room temperature. The cross-section and process flow for the IPCB are shown in Fig. 14. The IPCB process provides two metal layers (silver), printed capacitors (PVP), and resistors (carbon). We mount TFT circuits on an IPCB-interposer, which is then mounted on the main IPCB. The benefits of this modular prototyping approach are ease of testing and expandability.

Acknowledgement

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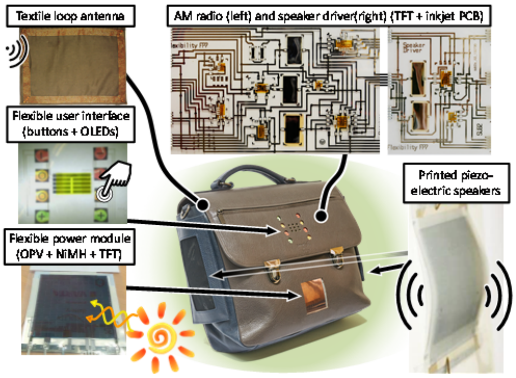


Fig. 1 Fully flexible modules of the heterogeneously integrated audio bag.

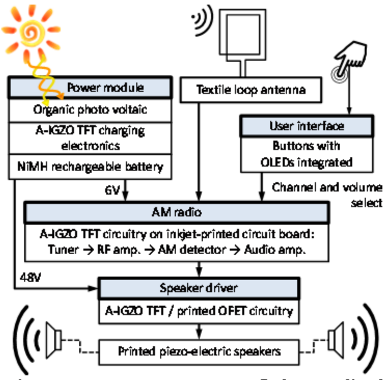


Fig. 2 System structure of the audio bag, where all components are flexible.

Audio bag main features	
Fully flexible heterogeneous system	
Wireless communication	
Audio playback	
Supply Voltage Vdd	6 V and 48 V (solar energy harvesting)
Overall a-IGZO TFT transistor count	126
Overall IPCB area	360 cm²

Fig. 3 Audio bag main features.

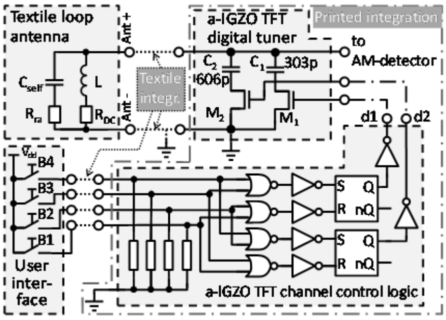


Fig. 4 Schematic of the digitally controlled tuner circuit and four-button channel control logic circuit.

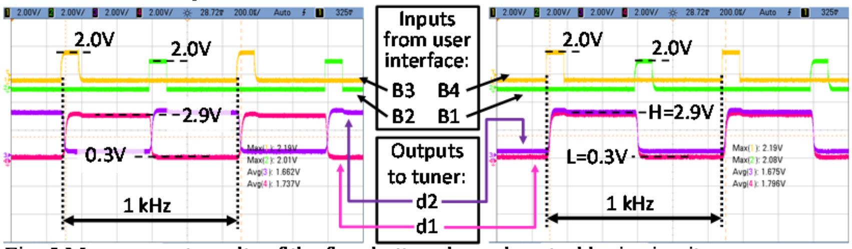


Fig. 5 Measurement results of the four-button channel control logic circuit.

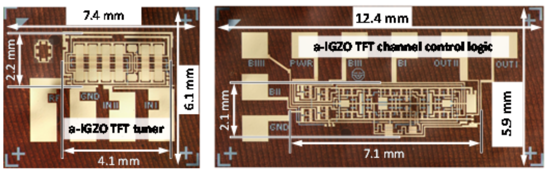


Fig. 6 Die photos of tuner and button control logic, showing core and cut frame dimensions.

{d1;d2}	{H;H}	{H;L}	{L;H}	{L;L}
f_0 [kHz]	226	271	340	802

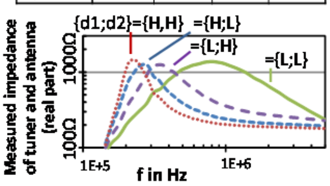


Fig. 7 Measured characteristics of tuner with antenna.

a-IGZO TFT circuit	Tuner	Channel logic
Range / Channels	909 pF / 4 channels	2-bit / 4 channels
Supply voltage Vdd	—	4 .. 6 V
Power consumption	—	< 2.9 mW (@V_{dd} = 4V)
Transistor count	2	44
Core chip area	9.0 mm²	14.9 mm²
Total chip area	45.1 mm²	73.2 mm²
Bending radius	> 5 mm	> 5 mm

Fig. 8 Features of tuner and button control logic.

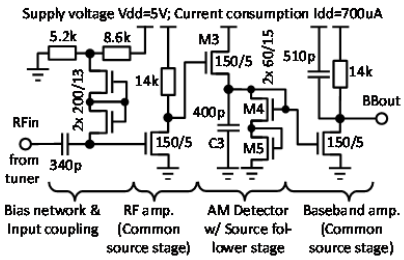


Fig. 9 Schematic of AM detector.

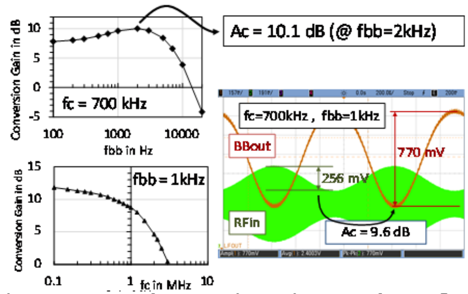


Fig. 10 Measured conversion gain Ac and waveform of AM detector (load condition: 1MΩ || 15pF).

Comparison AM detector	This work	[2]	Factor of improvement
Technology	a-IGZO TFT	a-IGZO TFT	
Supply voltage Vdd	5 V	5V	
Upper cutoff	ca. 1 MHz	> 20 MHz	Matched to audio bag antenna and tuner
Lower cutoff	< 100 kHz	ca. 1 MHz	
Conversion gain Ac	10.1 dB (3.2 x)	15.3 dB (5.8 x)	-5.2 dB (1/1.8)
Current at Vdd = 5V	***0.7 mA***	7.2 mA	10.3
Transistors	***7***	24	3.4
Stages	***2***	5	2.5
Core chip area	***5.7 mm²***	26.85 mm²	4.7

Fig. 11 Comparison of AM detector to previous work.

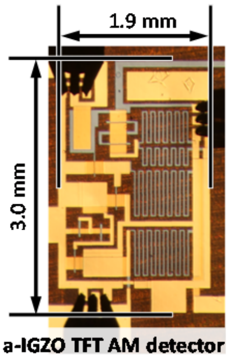


Fig. 12 Die photo of a-IGZO TFT AM detector (size with pads & cut-frame: 5.9 x 9.8 mm², not shown).

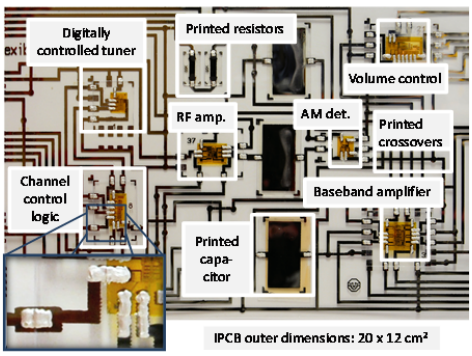
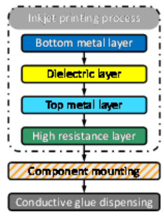


Fig. 13 Photograph of the fully flexible radio receiver, including digitally controlled tuner, channel control logic, AM detector, and baseband amplifier on an inkjet printed circuit board (IPCB).



Characteristic / Feature	Value
Resolution: min. lines and spaces	80 µm and 35 µm
Resistivity of interconnect (Cabot CCI-300 silver ink, cured at 150°C)	0.15 Ω/□
Resistivity of resistance layer (carbon)	25.8 kΩ/□
Relative permittivity of dielectric layer (cross-linked poly(4-vinylphenol), PVP)	4.5
Max. temperature during processing	150°C
Conductive glue	Polyurethane type
Substrates: – Polyethylene terephthalate (PET), polyethylene naphthalate (PEN), polyimide, paper, etc. – No preconditioning required	

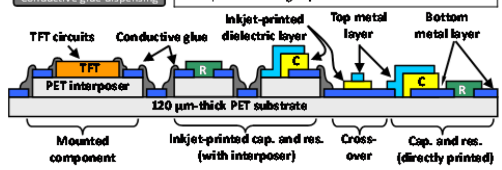


Fig. 14 Cross-section, process flow, and characteristics of inkjet printed circuit board (IPCB) integration technology.