A large-area, flexible, ultrasonic imaging system with a printed organic transistor active matrix

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Abstract:

We have successfully fabricated a large-area, flexible, ultrasonic system by integrating a two-dimensional polymeric ultrasonic sensing array with a printed organic transistor active matrix. The new sheet-type device can offer a cost-effective solution for a real-time three-dimensional imaging in free space and/or a large-area proximity sensor for robot skins.

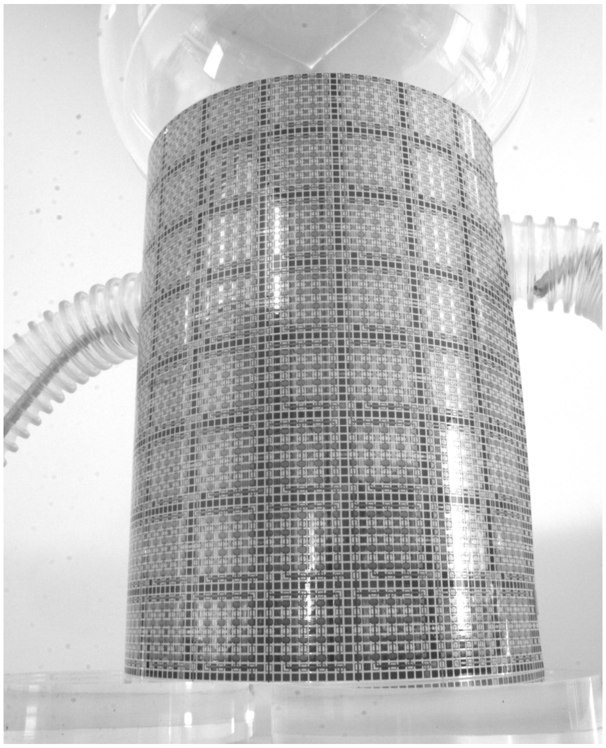

Fig. 1: Image of a printed organic transistor active matrix for ultrasonic imaging sheet. The sensing cells are formed by integrating a printed organic transistor sheet and an ultrasonic transducer array sheet. This system is mechanically flexible and can be wrapped around a body of robots.

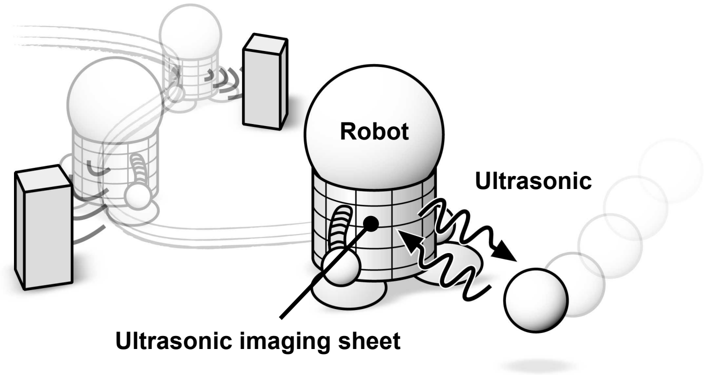

Fig. 2: Position sensing in free space. The ultrasonic system can detect approaching target objects without making contact with them. Furthermore, it can detect objects behind a cloth and/or a paper. This configuration is suitable for obtaining a viewing angle of 360º for a medium-length (several meters) proximity skin-like sensor.

Introduction

In the forthcoming ambient electronics era, multiple electronic devices used in human surroundings are expected to interact with people, objects, and the environment. In such a situation, the three-dimensional (3D) sensing of the position of people and objects in free space will be very important. Although position sensing in free space has commonly been carried out using light, radio, and millimeter waves, ultrasonic imaging can offer complimentary attractive features such as a simple architecture and real-time nondestructive 3D imaging in free space at an ultralow cost.

In this study, we have successfully fabricated a large-area, flexible, ultrasonic 3D imaging system, for the first time, by integrating an ultrasonic transducer array sheet with a printed organic field-effect transistors (FETs) active matrix. The printed transistors ($\mu \sim 0.5$ cm^2/Vs) with a grounded gate can switch 40 kHz signals with an on/off ratio of greater than 10^4. The system comprises 8 × 8 ultrasonic sensing cells or others, with a printed area of 25 × 25 cm^2. 3D ultrasonic images can be obtained for multiple target objects over this sheet. This system can detect target objects behind a cloth and a paper. It is mechanically flexible and can be wrapped around a cylindrical bar, as shown in Fig. 1; this configuration is suitable for obtaining a viewing angle of 360º for a medium-length (~ several meters) proximity robotic skin-like sensor.

Device manufacturing process

The ultrasonic sensing cell comprises one organic transistor and one ultrasonic transducer (Fig. 3). A transistor active matrix sheet and an ultrasonic transducer array sheet (Fig. 4) are manufactured separately and electrically connected to each other. The circuit diagram is shown in Fig. 5.

A. Printed organic transistor active matrix

The organic transistors (1-3) are fabricated on a 75-µm-thick polyimide film. The source, drain, and gate electrodes are deposited by an inkjet printing or a vacuum evaporation. A 500-nm-thick polyimide gate dielectric layer is formed by inkjet or spin coating, and a 50-nm-thick pentacene channel layer is deposited by vacuum evaporation by using a printed shadow mask.

B. Ultrasonic transducer array sheet

A 28-µm-thick piezoelectric polyvinylidene fluoride (PVDF)

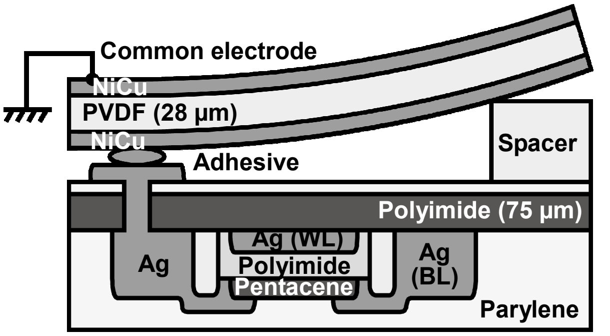

Fig. 3: Cross-sectional view of an ultrasonic sensing cell. An organic transistor active matrix is laminated with an array of an ultrasonic transducer using a silver paste. The ultrasonic transducer is bended by the spacer to improve the sensitivity.

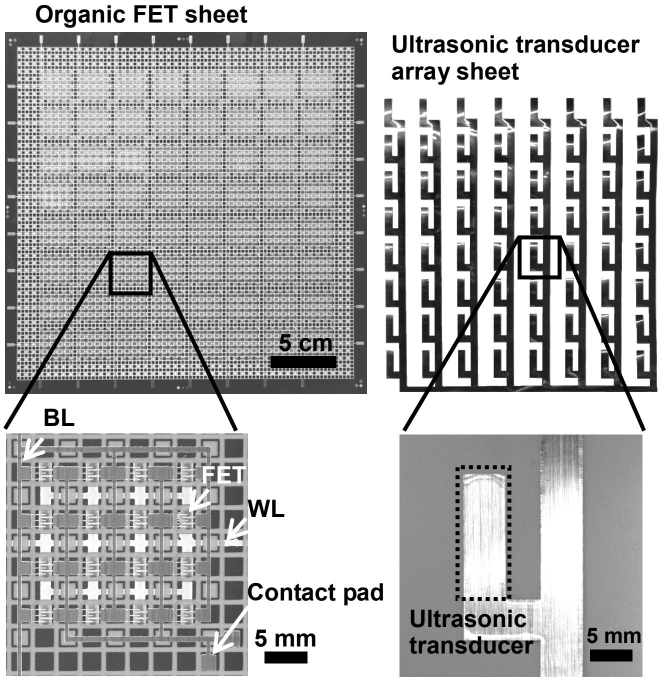

Fig. 4: Photographs of the ultrasonic imaging sheet. The dimensions of the ultrasonic transducer are 5 mm × 10 mm (W × L); it is patterned using a numerical controlled cutting system. In order to achieve a low channel resistance, 16 transistors are connected in parallel.

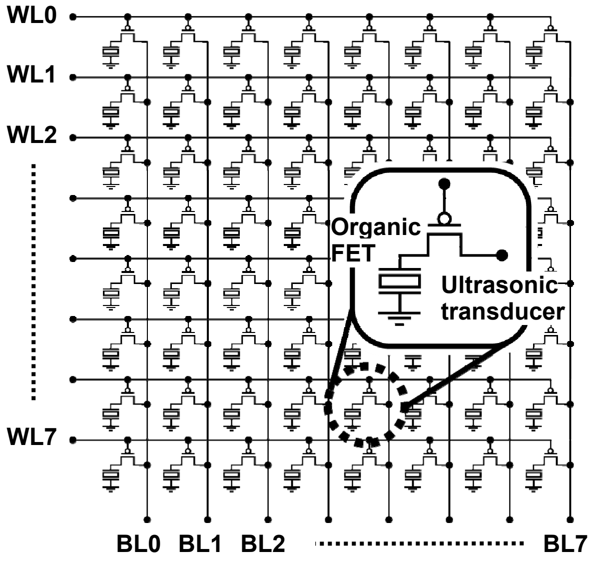

Fig. 5: Circuit diagram. Each sensing cell has one ultrasonic transducer and one transistor. The sensing cells are spaced by intervals of 1 inch.

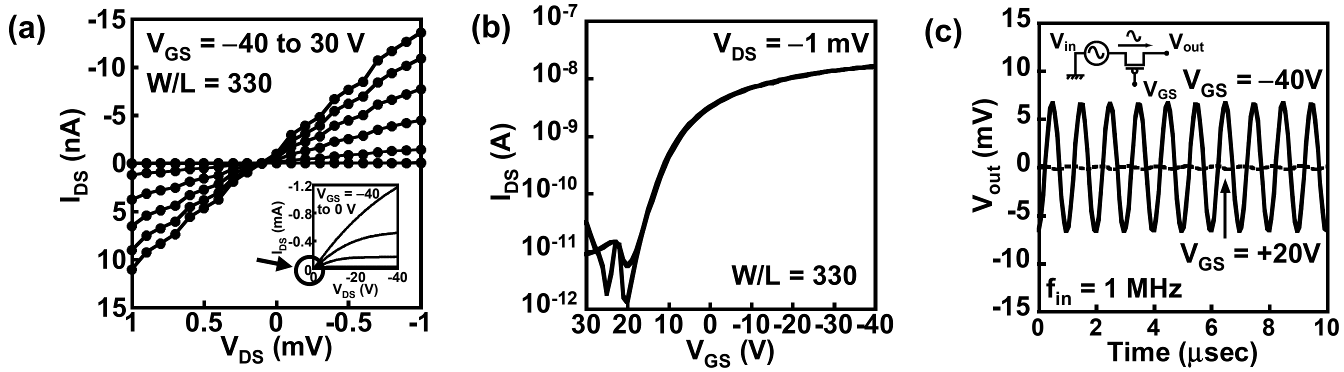

Fig. 6: High-speed printed organic FETs. (a) Operation of the organic FETs with a small source-drain voltage (V_{DS}). A plot of the source-drain current (I_{DS}) vs. V_{DS}. (b) I_{DS} vs. gate-source voltage (V_{GS}) of the organic transistors in a linear regime (V_{DS} = −1mV). (c) 1 MHz operation of the organic FETs with a grounded-gate.

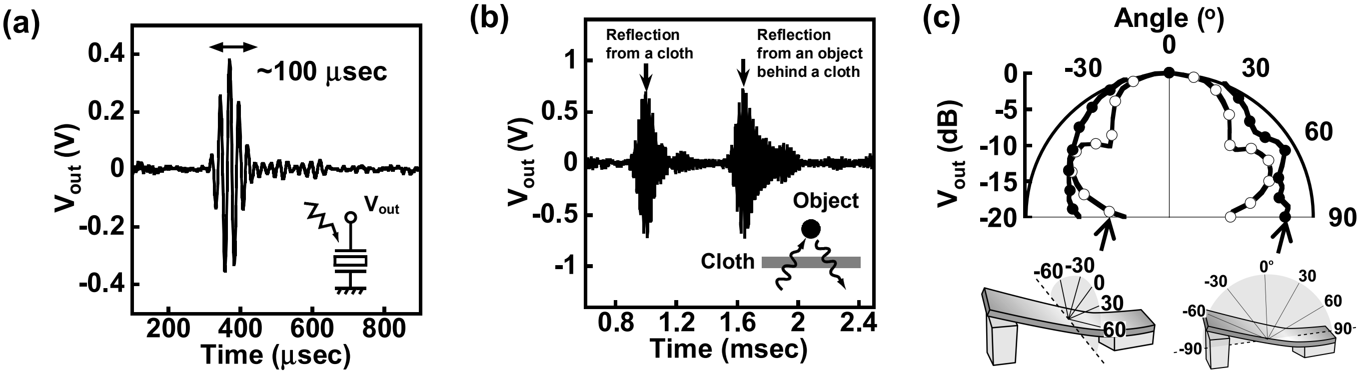

Fig. 7: Stand-alone ultrasonic transducer. (a) A typical waveform (V_{out}) received at the transducers. The signal is amplified by a 40-dB gain AC amplifier. The frequency of the transmitting signal is 40 kHz. (b) Received waveform reflected from a stiff object behind a cloth. (c) Angular dependence of V_{out}. The ultrasonic transducers can detect signals in an angle of 180°.

film (4), whose surfaces are covered by metal, is used as a sheet-type ultrasonic transducer. The transducers are used in the bending mode (d_{31} mode). To adjust the mechanical resonance frequency to 40 kHz, the transducer is bended to improve the sensitivity using a spacer sheet.

Device characteristics

A. High-speed printed organic FETs (Fig. 6)

The mobility in the saturation regime is 0.5 cm^2/Vs, while an on/off ratio is 10^7 in DC measurements. The transistors operate efficiently in the small signal regime of the ultrasonic transducers (~1 mV_{p-p}). The transistors with the grounded gate can switch 40 kHz signals with an on/off ratio of greater than 10^4.

B. Stand-alone ultrasonic transducer (Fig. 7)

The ultrasonic transducer has an output voltage of ~0.8 V_{p-p} and a narrow pulse width of ~100 μs after an amplification of 40 dB by the incidence of an ultrasonic wave. The ultrasonic transducers can detect a stiff object that is hidden inside a cloth. It also shows broad directivity (>-5 dB for ± 60°).

C. Integrated imaging system (Fig. 8)

The characteristics of the integrated ultrasonic sensing cell comprising one ultrasonic transducer and one organic FET are examined. The signal from the ultrasonic transducer is switched by the organic FET at 40 kHz. Crosstalk is characterized (Fig. 8c). The integrated sensing cells have an on/off ratio of 10^4 at 40 kHz.

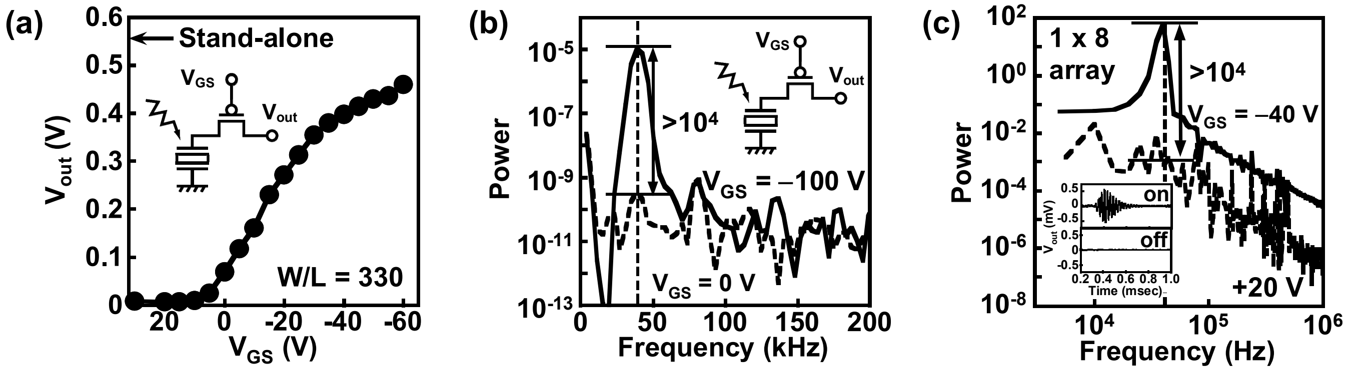

Fig. 8: Ultrasonic sensing cells comprising organic FETs and ultrasonic transducers. (a) Switching characteristics of the ultrasonic sensing cell with changing V_{GS} of the organic transistor. (b) Power spectrum of the ultrasonic sensing cell for V_{GS} = –100 V (solid line) and 0 V (dashed line). The on/off ratio exceeds 10^4. (c) An ultrasonic sensing cell connected to a 1 × 8 ultrasonic sensing array also exhibits an on/off ratio exceeding 10^4.

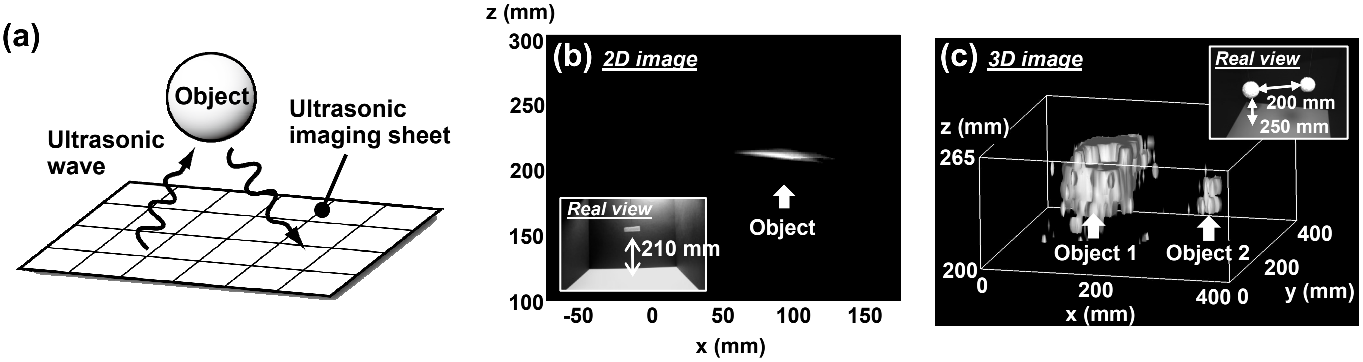

Fig. 9: Ultrasonic imaging. (a) Experimental setup of ultrasonic imaging. A 3D image of the object can be reconstructed (synthetic aperture method) using all the received signals. (b) 2D image obtained by a 1 × 8 ultrasonic sensing array comprising ultrasonic transducers and organic transistors. (c) 3D image obtained by 17 × 11 stand-alone ultrasonic transducers.

D. Imaging (Fig. 9)

We have successfully constructed clear 2D and 3D images by the manufactured sheet devices. The imaging was explored at 40 kHz that is suitable for free-space sensing; however, the similar system will be feasible for a ultrasonic medical diagnostic (5) if on/off ratio of the transistors are optimized at the carrier frequency of 2 MHz.

Acknowledgement

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