Cut-and-Paste Organic FET Customized ICs for Application to Artificial Skin

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Abstract

A flexible and large-area pressure sensor suitable for artificial skin applications has been fabricated using organic transistors and rubbery sensors integrating row decoders, column selectors and a pressure-sensitive array. Cut-and-paste customizability is first introduced in designing the organic circuits, which makes the circuit scalable and realizes an arbitrary size of the area sensor using the same sheet of organic circuits by cutting and pasting with a connecting plastic tape.

Organic transistor circuits are attracting attention for complementing the high-performance yet expensive silicon VLSIs [1, 2, 3]. The organic FETs (OFETs) are characterized by several features. First, fabrication cost of organic circuit is low even for large area electronics. Secondly, flexible circuits can be realized. Lastly, carrier mobility is about three orders of magnitude lower than silicon and the resultant circuit is slow in speed. The slow speed may not fit for video and RF applications. All these features, however, are suitable for most of area sensor applications. Among area sensors, sensing of a touch is important for robots of the next generation and wireless sensor network. Thus artificial skin integrating pressure sensors and peripheral electronics using OFETs is fabricated for the first time based on the scalable circuit concept whose feasibility has been demonstrated in this paper.

Device structure and fabrication process are described in Fig. 1. First, gold gate electrodes are patterned with the conventional photolithography and lift-off process (or shadow mask technique) on a 75-μm thick polyethylene naphthalate (PEN) or polyimide (PI) film with super low shrinkage for soldering afterwards. Then, PI insulator is spin-coated with rotation speed of 3000rpm on the film and cured at 180C for 1hr in an oven under the nitrogen environment. Then, some part of PI film is removed by a CO_2 laser drill machine to make via holes. Next, pentacene is deposited through a shadow mask on the film by vacuum sublimation at the pressure of 30μPa at ambient substrate temperature. The nominal thickness of the pentacene layer is 30nm. The chemical structure of pentacene is shown in the figure. Gold is evaporated on the film to form source/drain electrodes (top contact geometry).

To complete the integration, above-mentioned OFETs are stacked with pressure sensors. The pressure sensors are made of pressure-sensitive conductive rubbery sheets sandwiched between a copper-coated PI film and another PI film with two-dimensional via hole matrix with round diameter of 100μm and spatial periodicity of 2.54mm (0.1in). The via holes are fabricated on the PI films by the conventional method similar to flexible circuit boards; combination of chemical etching, drilling and plating. The pressure-sensitive sheet is 0.5-mm thick silicone rubber containing graphite. Resistance changes from 10MΩ to 100Ω, depending on the pressure applied to the sheet. Finally, encapsulation of the whole device is done by polyethylene terephthalate (PET) film laminated in nitrogen ambient.

Fig. 2 shows measured V_{DS}-I_{DS} characteristics of the fabricated PMOS OFET. Only PMOS is used in the circuit design. The measured curves are reproduced quite well by SPICE MOS model level 1 with serial resistors of 200kΩ. The model is used in the SPICE simulation afterwards. I_{DS} did change in time but with the material and the structure used here, the rapid change occurs in a minute and after the initial change, I_{DS} change and hysteresis do not affect the circuit operation. Since the OFET characteristics are fluctuated by fabrication, fixed ratio type of circuits are eliminated in designing the system.

A circuit diagram of the area sensor system is shown in Fig. 3, which has three parts; a sensor matrix, row decoders and column selectors. Three parts are fabricated separately and connected with a PET film with evaporated gold stripes of 0.1-in pitch and conductive glue called a connecting tape, which enables the cut-and-paste customization of the area sensor size. The sensor matrix consists of 16 x 16 pressure-sensitive cells, whose size is 0.1in x 0.1in. In the diagram, a 16 x 16 case is depicted but if a small area sensor of 4 x 4 cells is needed, the circuit is cut along a rectangle specified by a dashed line and the cut-down version of the area sensor works without modification. This is because the row decoder and the column circuit are carefully designed and laid out so that any 4n x 4n ($n \leq 4$) cell matrix can be driven just by cutting out required part from the sheet of circuit. At the edge of every 4 rows and 4 columns, wires are slightly widened to make the connection by the connecting tape easier. If the required shape of the sensor matrix is not rectangular, it is also possible to cut and remove a corner as far as the sensor matrix is convex.

The customization through cut and paste is preferable because there is no need to make a new mask depending on the required size and shape. This reduces the turn-around-time and cost. Although the fabricated circuit in this paper has the 16 x 16 cells, the concept can be expanded to arbitrarily large size. A long sheet of row decoders, a long sheet of column selectors and a large area sensor matrix are fabricated and prepared in advance. When the required size and shape is fixed, an appropriate part of the circuit are cut out from the pre-fabricated sheets and then glued together by the connecting tape.

Fig. 4a shows a measured pressure dependence of static current flowing through the sensor cell. When the area sensor is pushed by a rectangular object, only corresponding part of the pressure-sensitive rubber turns on and the corresponding cells pull the bit lines up to V_{DD} as shown in Fig. 4b.

Fig. 5 is measured operation waveforms of the area sensor. The delay from row decoder activation signal ϕ_R-bar to bit-out is 23ms. Since 4-bit data are read out in parallel, less than 2 seconds is needed to scan over 16 x 16 sensor cells. The delay dependence on V_{DD} is shown in Fig. 6. With increasing V_{DD} up to 100V, the delay can be reduced to about a half. The measured points are compared with the simulation using the above-mentioned SPICE model. There is a room for an order of magnitude reduction in delay by decreasing channel length, reducing the line width of word lines and other bus lines to reduce capacitance and making the logic threshold voltage of the external circuit which senses the bit-out signal to 10V instead of 20V.

Fig. 7 shows a photograph of the artificial skin system consisting of the 16 x 16 sensor matrix, the row decoders and the column selectors glued with the connecting tapes. The system can be bent down to 5mm in radius, which is sufficient to wrap around the surface of a round object like a robot. The change of the OFET current caused by bending is measured using a bare OFET without a pressure-sensitive rubber and encapsulation. With the bending around a bar of 5-mm in radius, the current is decreased less than 3%, when the organic material is incurred a stretching force. The transistor is fully functional even with the bending of down to 1mm in radius. This demonstrates the feasibility of mechanically flexible circuits.

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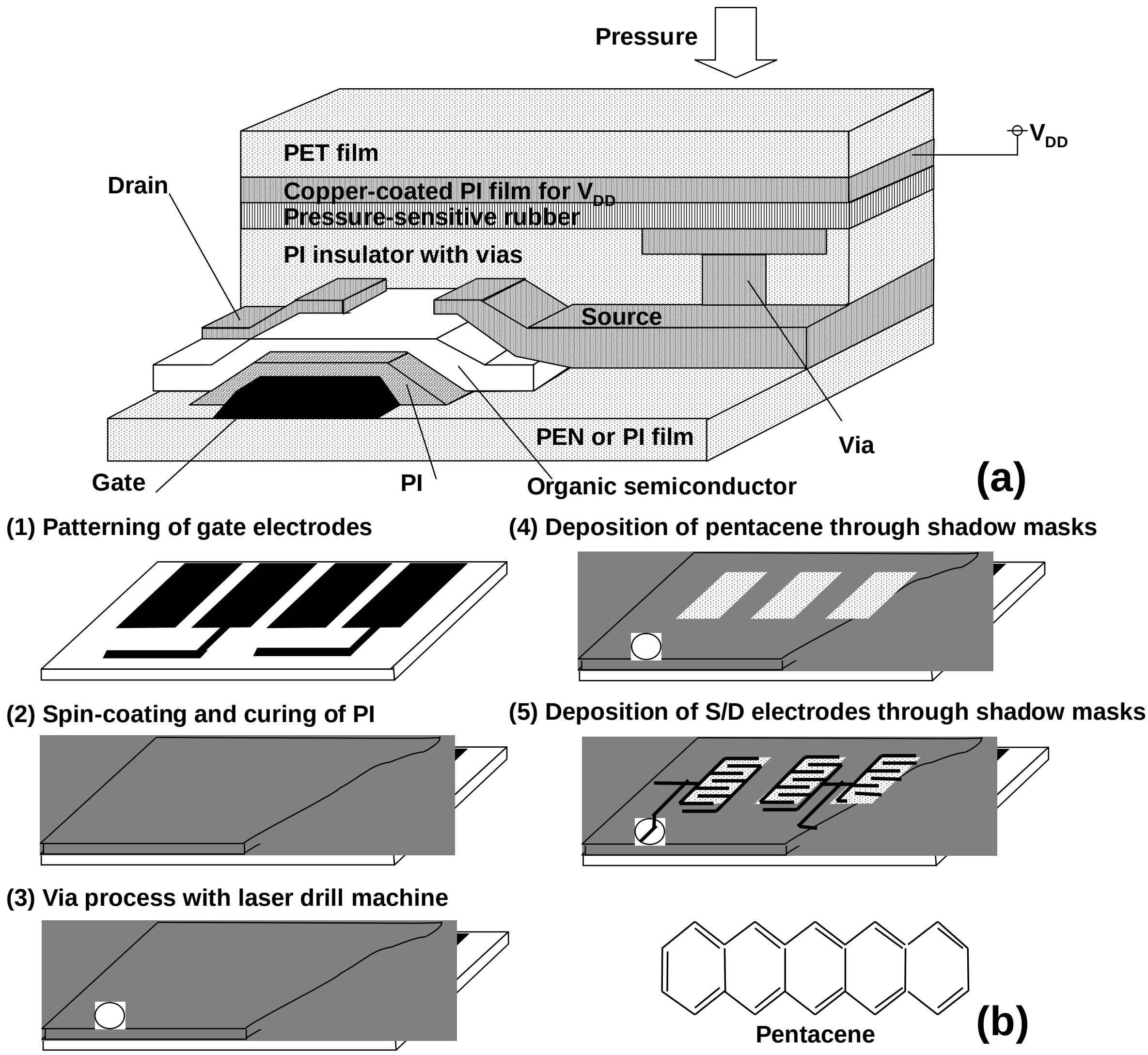

Figure 16.2.1:

Figure 1: (a) Device structure, (b) process flow with chemical structure of pentacene

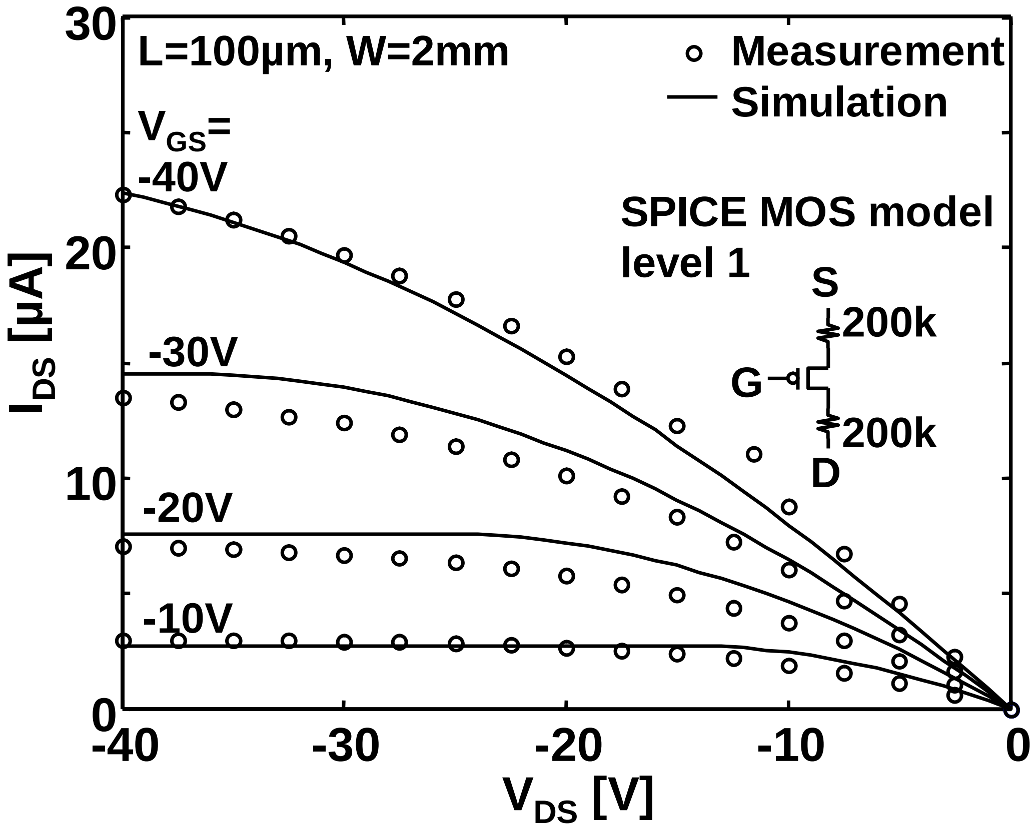

Figure 16.2.2:

Figure 2: I_{DS}-V_{DS} of fabricated PMOS OFET

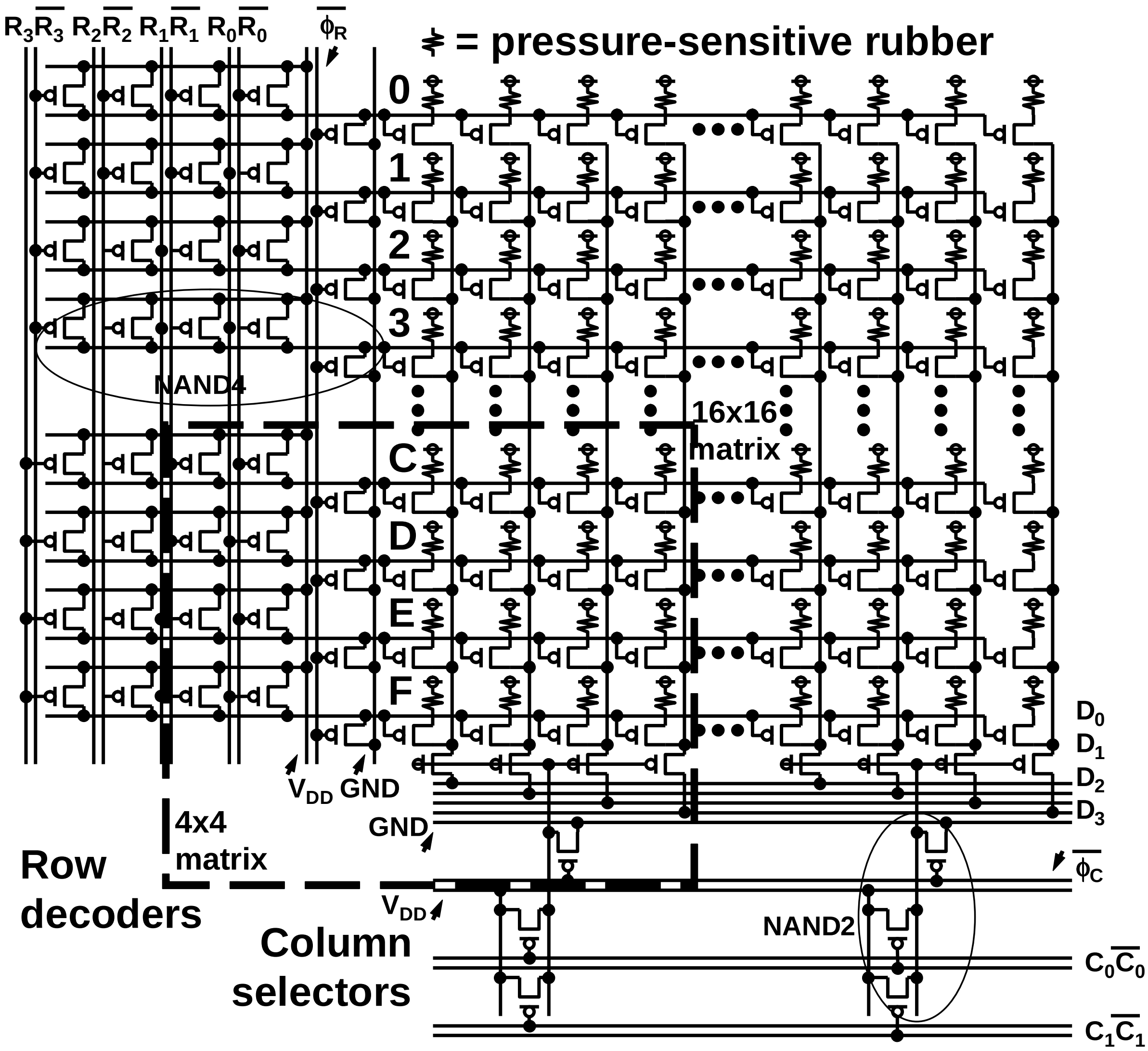

Figure 16.2.3:

Figure 3: Circuit diagram

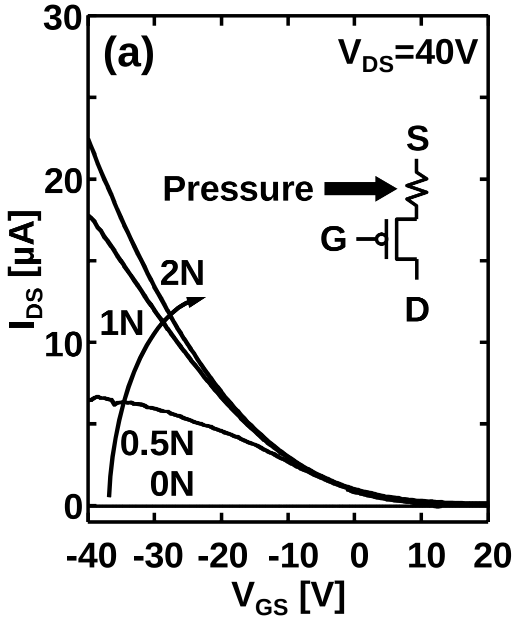

Figure 16.2.4:

Figure 4: (a) Pressure dependence of sensor cell, (b) bit-out when a part of area sensor is pressed

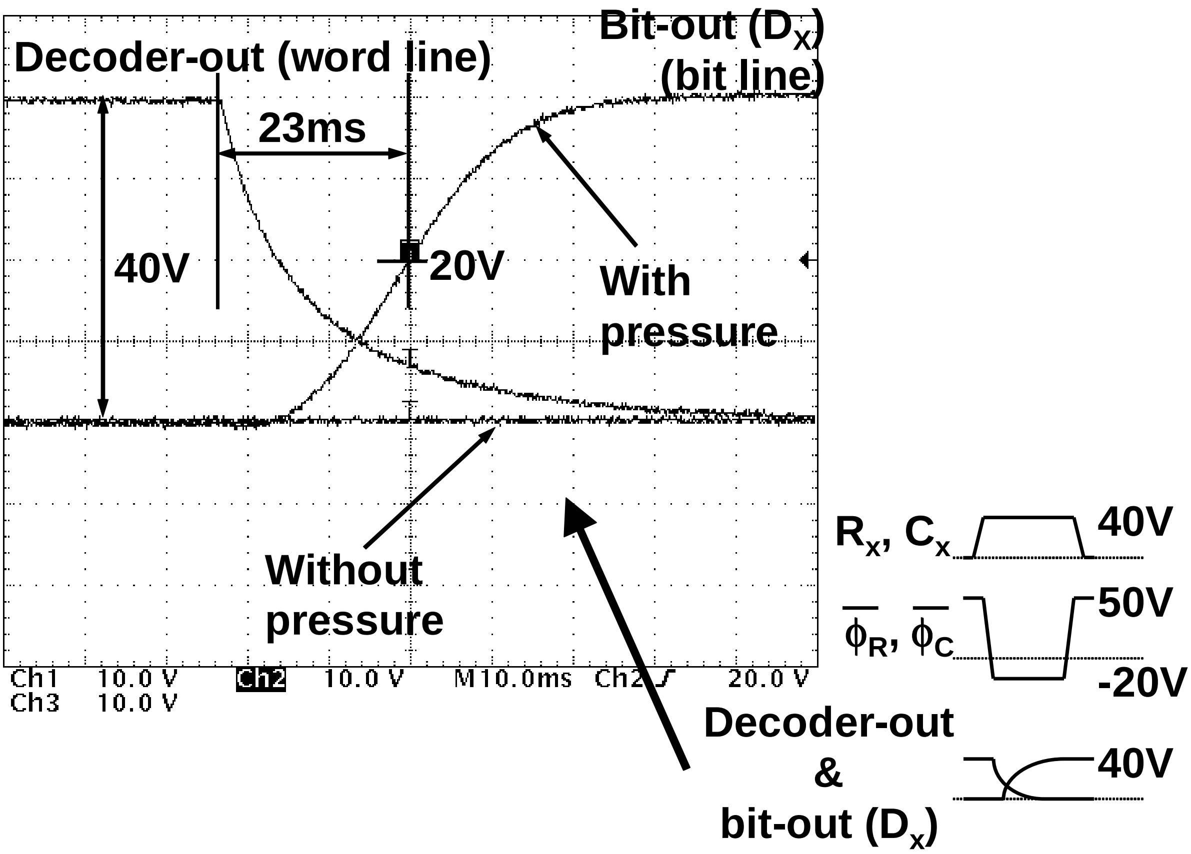

Figure 16.2.5:

Figure 5: Operation waveforms

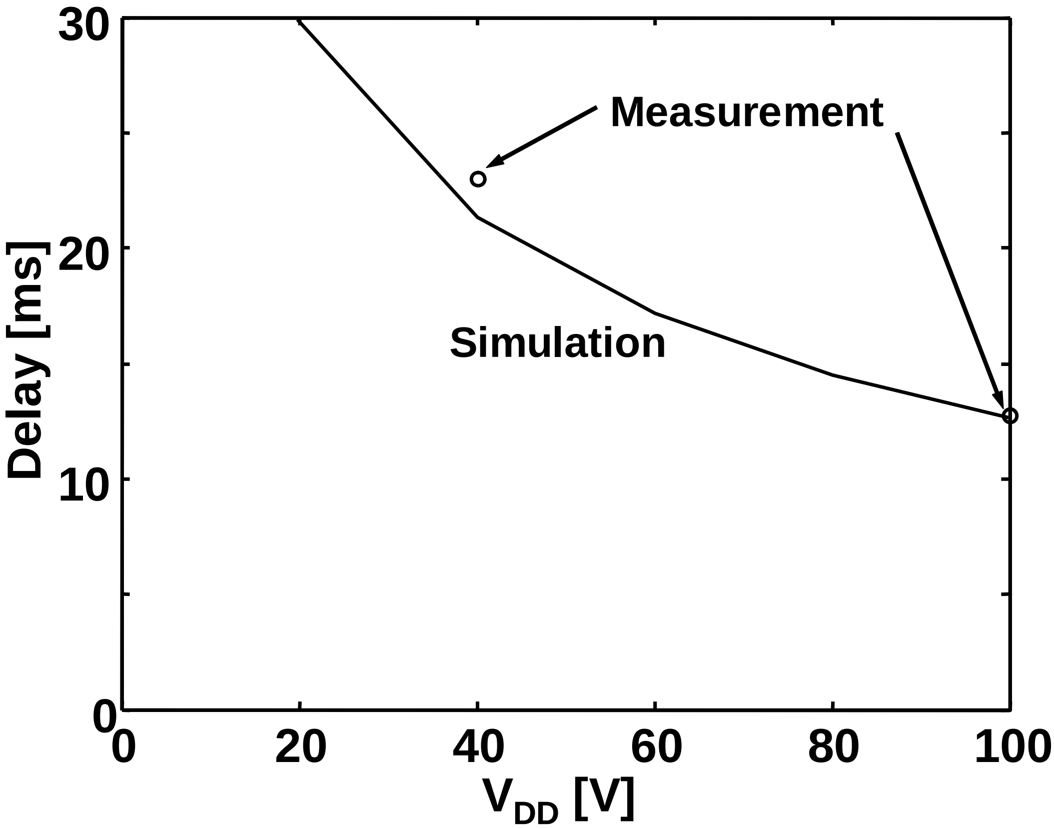

Figure 16.2.6:

Figure 6: Delay dependence on V_{DD}

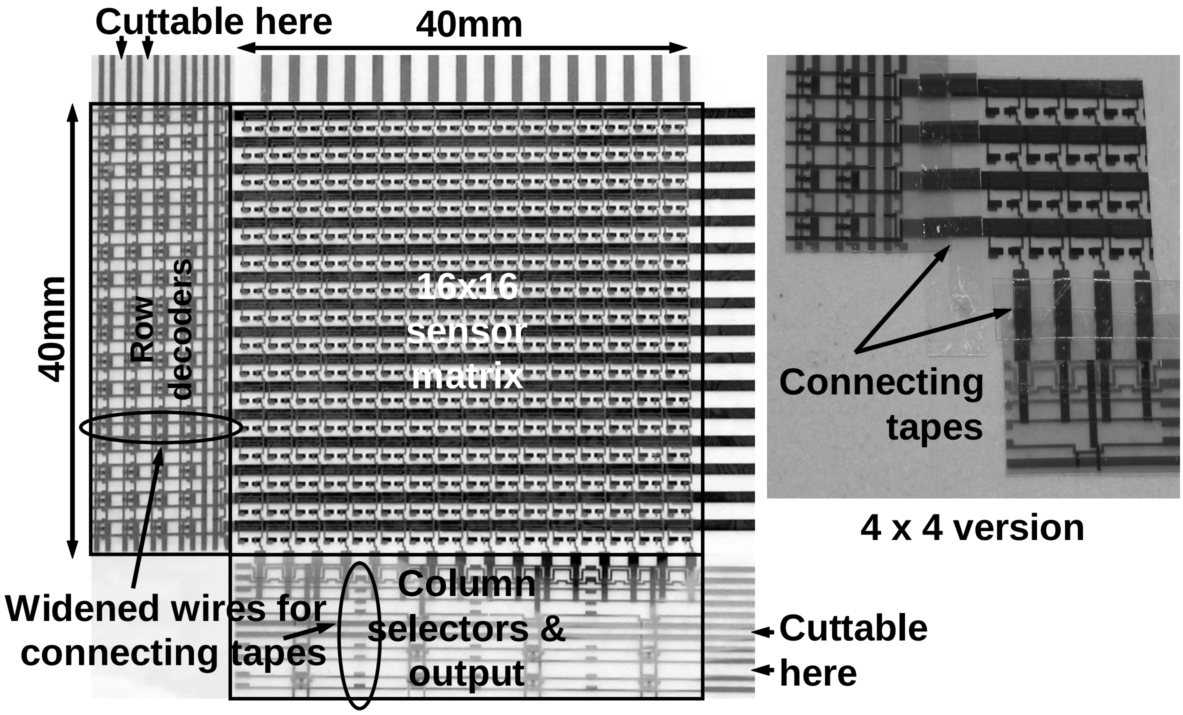

Figure 16.2.7:

Figure 7: Photograph of fabricated artificial skin system