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

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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 an 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 be suitable for video and RF applications; however, these features are suitable for most sensor applications. Sensing touch is important for the next generation of robots. Quite recently we have fabricated a flexible, area pressure sensor matrix with integrating rubbery pressure sensors and OFETs [4]. In this paper, we demonstrate a scalable circuit concept of constructing decoders and peripheral circuits by use of cut-and-paste programmability of organic circuits for application to artificial skin.

Device structure and the fabrication process are described in Fig. 16.2.1. First, gold gate electrodes are patterned with a conventional photolithography and lift-off process (or shadow mask technique) on a 75µm thick polyethylene naphthalate (PEN) or polyimide (PI) film with super low shrinkage for subsequent soldering. Then, the PI insulator is spin-coated with a rotation speed of 3000rpm on the film and cured at 180°C for 1hr in an oven in a nitrogen environment. Then, some part of PI film is removed by a CO_2 laser drill for the via holes. Pentacene, whose chemical structure is shown in Fig. 16.2.1, is deposited next 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. Gold is evaporated on the film to form source/drain electrodes (top contact geometry).

To complete the integration, the 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 a 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, i.e., a combination of chemical etching, drilling and plating. The pressure-sensitive sheet is 0.5mm thick silicone rubber containing graphite. Resistance changes from 10MΩ to 100Ω, depending on the pressure applied to the sheet. Finally, the whole device is encapsulated by a polyethylene terephthatlate (PET) film in a nitrogen ambient.

Figure 16.2.2 shows measured V_{DS}-I_{DS} characteristics of the fabricated PMOS OFET used exclusively in this design. The measured curves are in good agreement with the Level 1 SPICE MOS model with 200kΩ series resistors. I_{DS} did change in time but, with the material and the structure used here, the rapid change occurs in a minute. After the initial change the I_{DS} change and hysteresis do not affect the circuit operation. Since the OFET characteristics vary with fabrication, fixed ratio type circuits are eliminated in designing the system.

A circuit diagram of the area sensor system is shown in Fig. 16.2.3, which has three parts; a sensor matrix, row decoders and column selectors. The three parts are fabricated separately and connected with a PET film with evaporated gold stripes of 0.1in 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 4m x 4n (m, n≤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 to 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 long as the sensor matrix is convex.

Customization through cut and paste is preferable because there is no need to make a new mask for each new size and shape. This reduces the turn-around-time and cost. Although the fabricated circuit in this paper has 16 x 16 cells, the concept can be expanded to arbitrarily large size. Long sheets of both row decoders and 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 is cut out from the prefabricated sheets and glued together by the connecting tape.

Figure 16.2.4a shows the measured pressure dependence of static current flowing through the sensor cell. When the area sensor is pushed by a rectangular object, only the 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. 16.2.4b.

Figure 16.2.5 depcits the measured operational waveforms of the area sensor. The delay from the row decoder activation signal $\bar{\phi}_R$ to bit-out is 23ms. Since 4b data are read out in parallel, less than 2s is needed to scan 16 x 16 sensor cells. The delay dependence on V_{DD} is shown in Fig. 16.2.6. Increasing V_{DD} to 100V, the delay reduces to about a half. The measured points are compared with the simulation using the above-mentioned SPICE model. An order of magnitude reduction in delay is possible 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 10V instead of 20V.

Figure 16.2.7 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 pressure-sensitive rubber and encapsulation. With the bending around a bar of 5mm in radius, the current is decreased less than 3% when the organic material incurs a stretching force. The transistor is fully functional even with bending to 1mm radius. This demonstrates the feasibility of mechanically flexible circuits.

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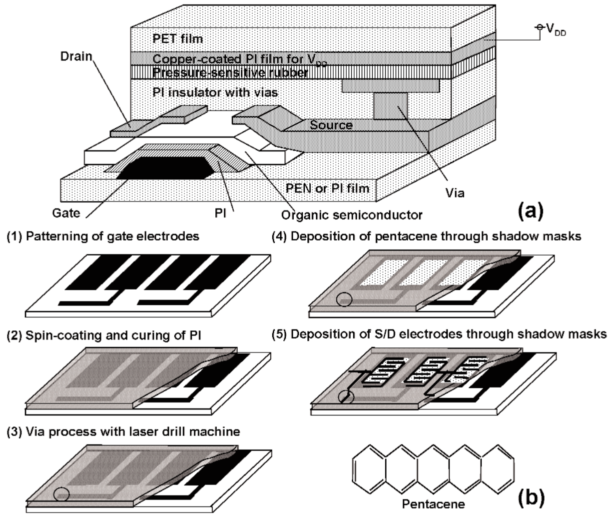


Figure 16.2.1: (a) Device structure, (b) process flow with chemical structure of pentacene.

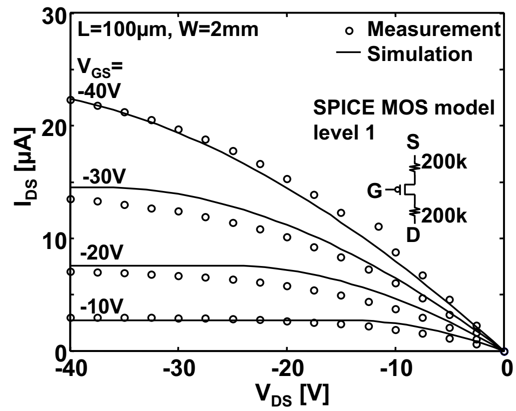


Figure 16.2.2: I_{DS}-V_{DS} of fabricated PMOS OFET.

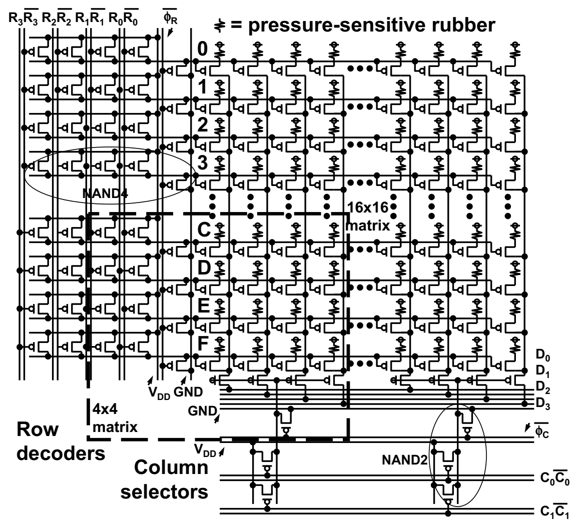


Figure 16.2.3: Circuit diagram.

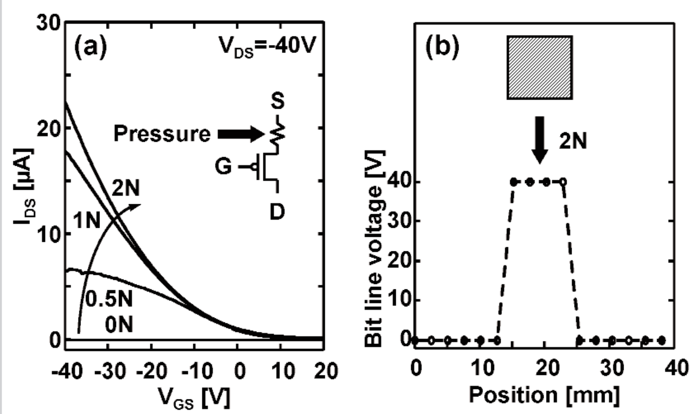


Figure 16.2.4: (a) Pressure dependence of sensor cell, (b) bit-out when a part of area sensor is pressed.

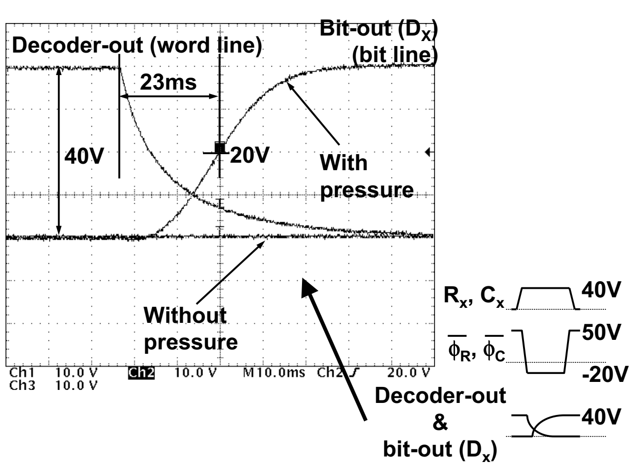


Figure 16.2.5: Operational waveforms.

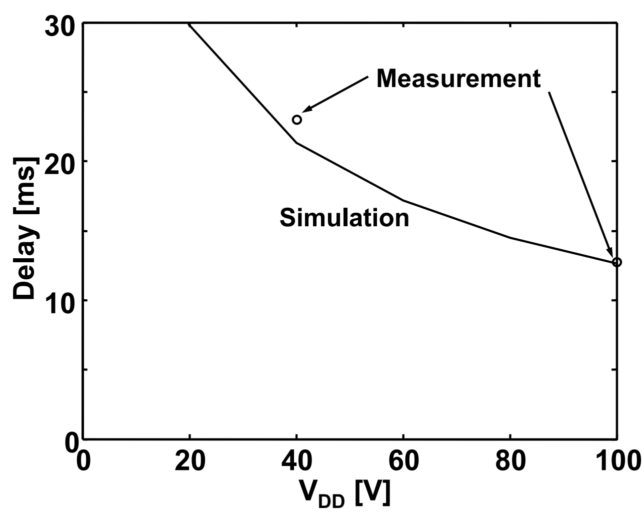


Figure 16.2.6: Delay dependence on V_{DD}.

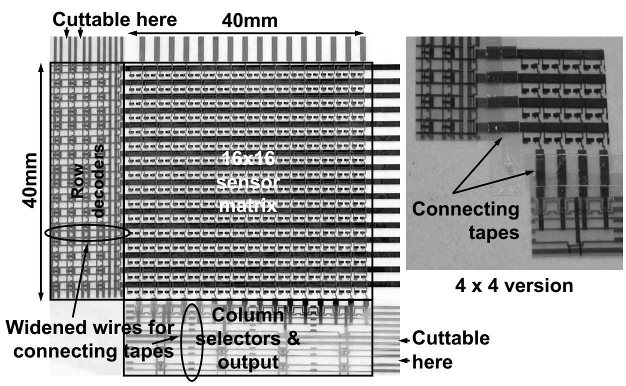
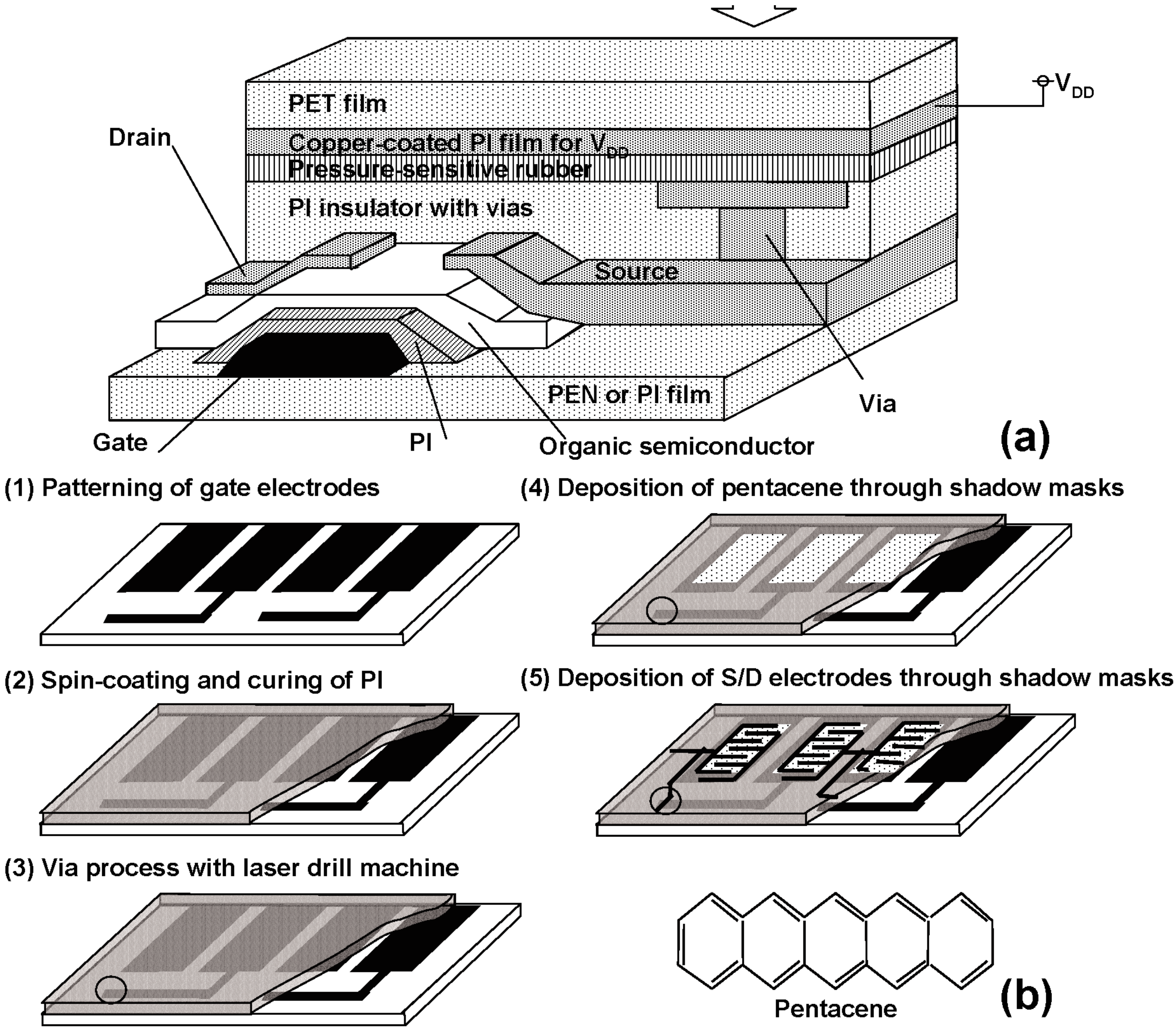


Figure 16.2.7: Photograph of fabricated artificial skin system.



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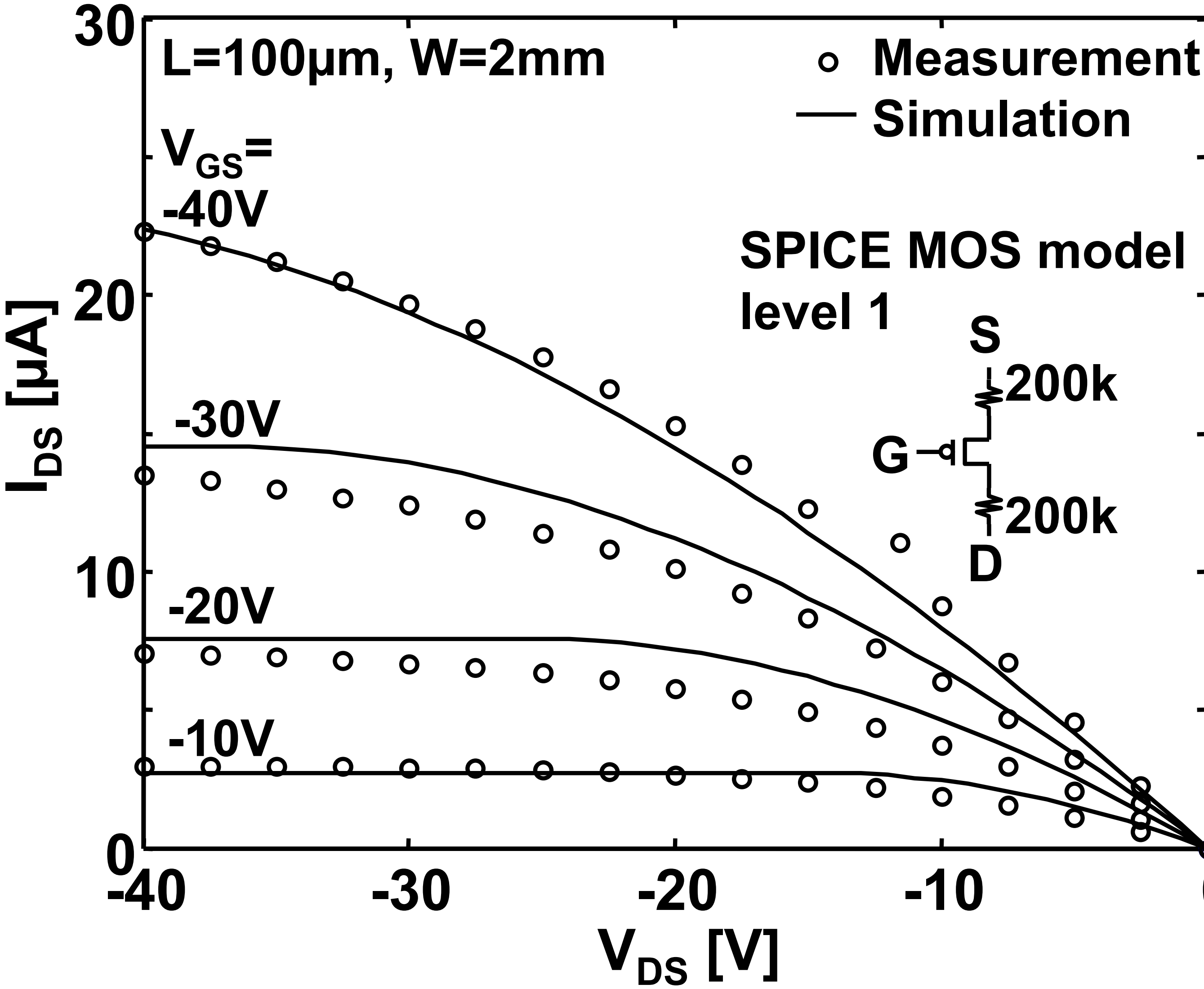

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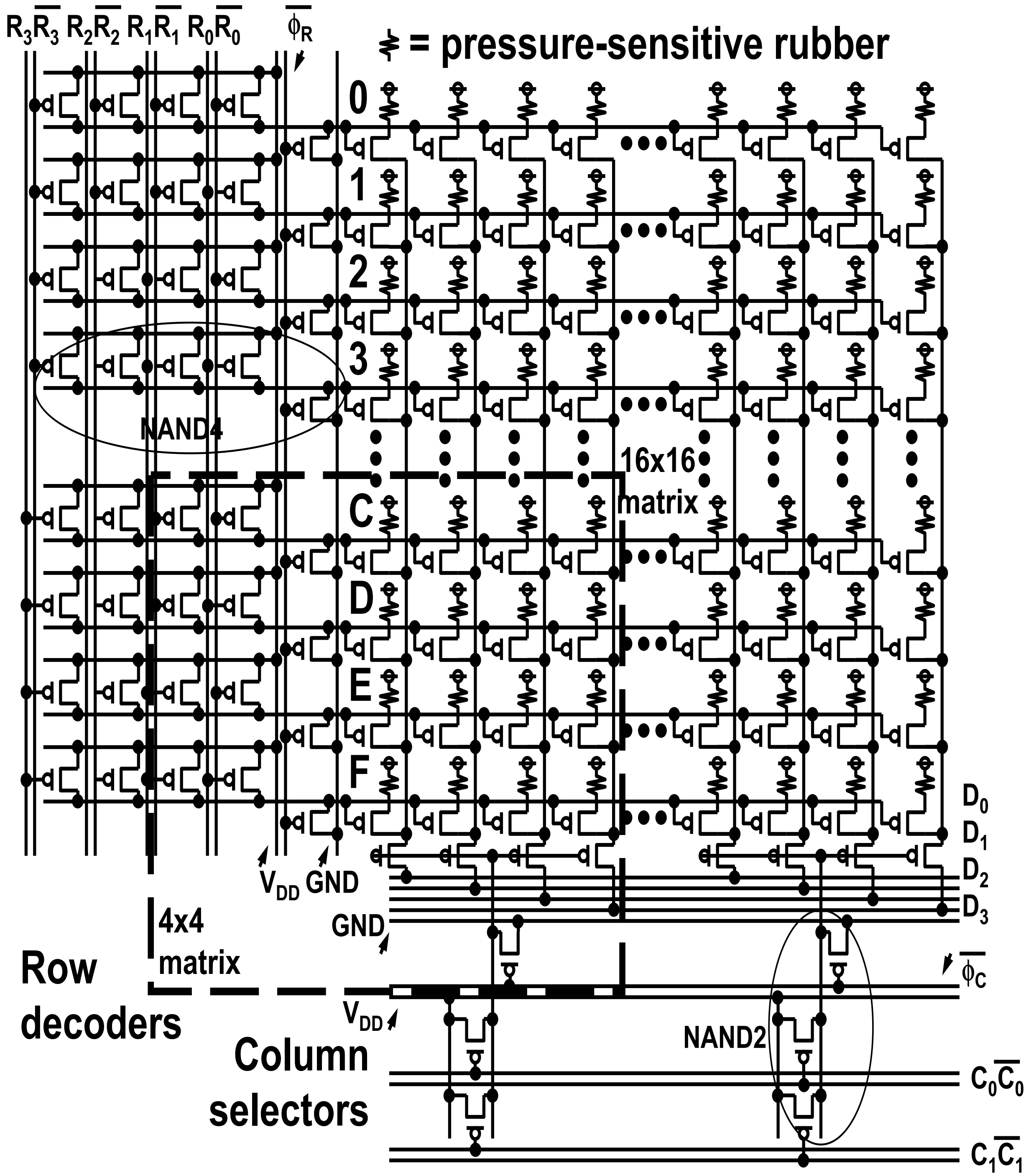

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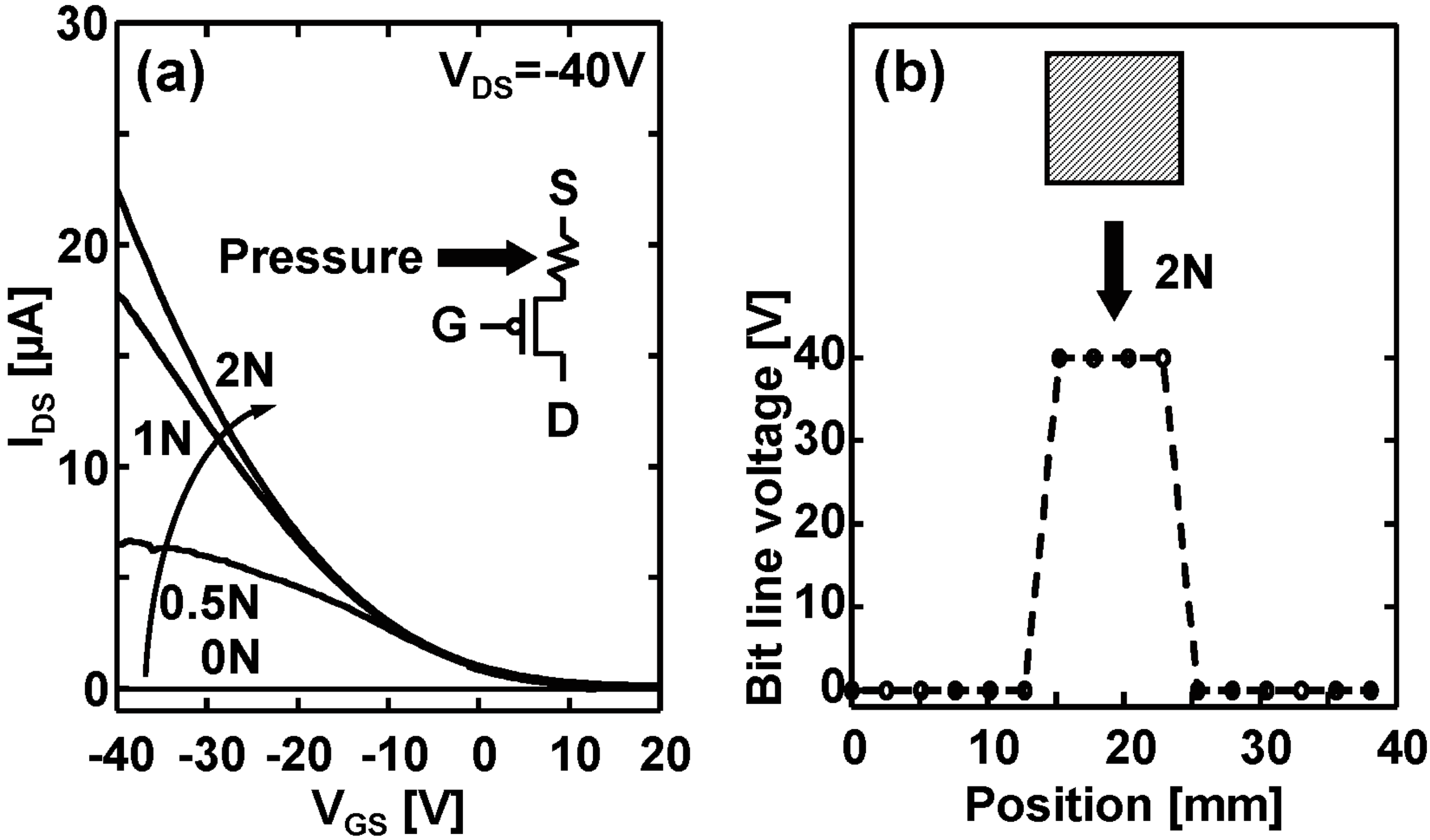

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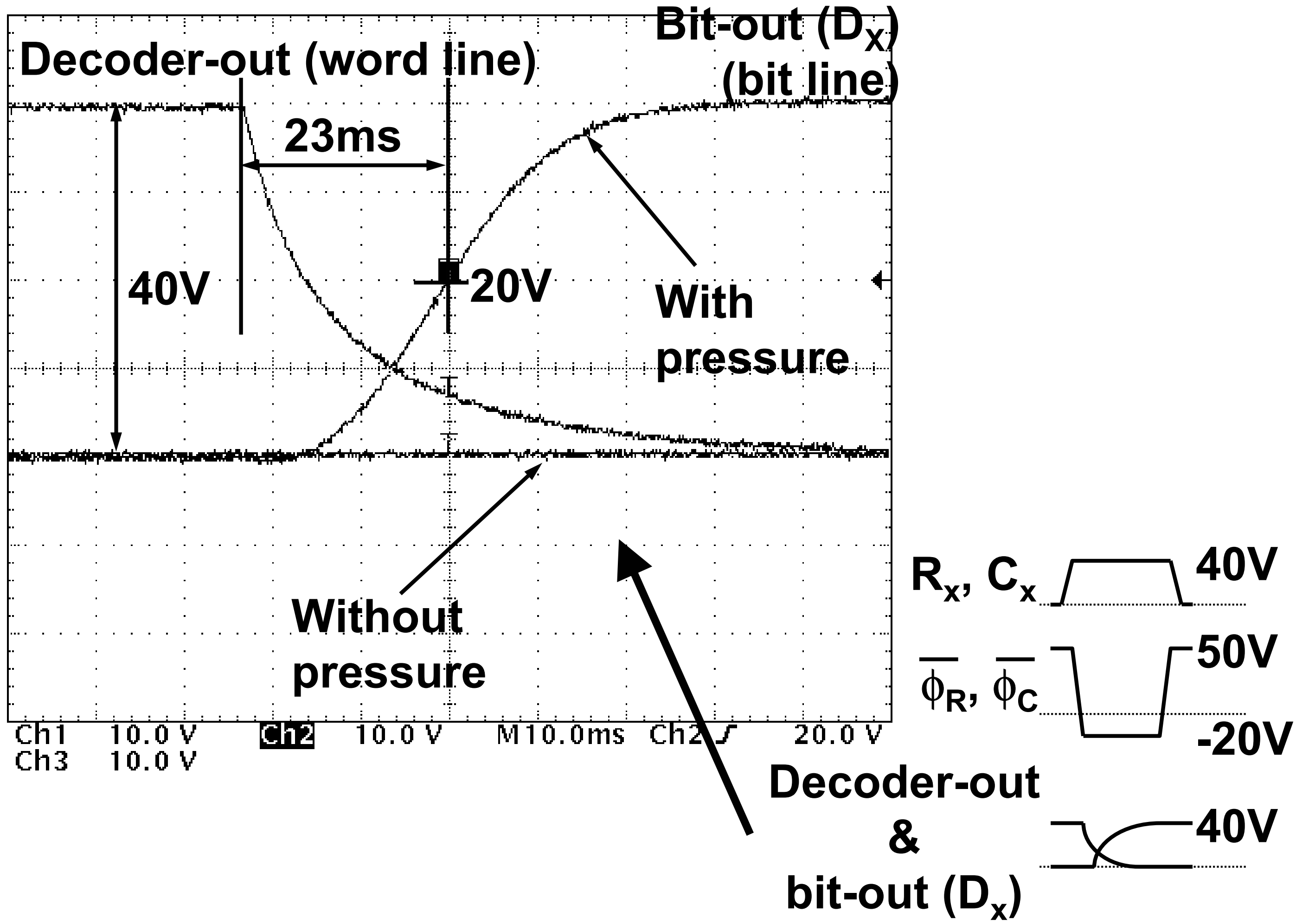

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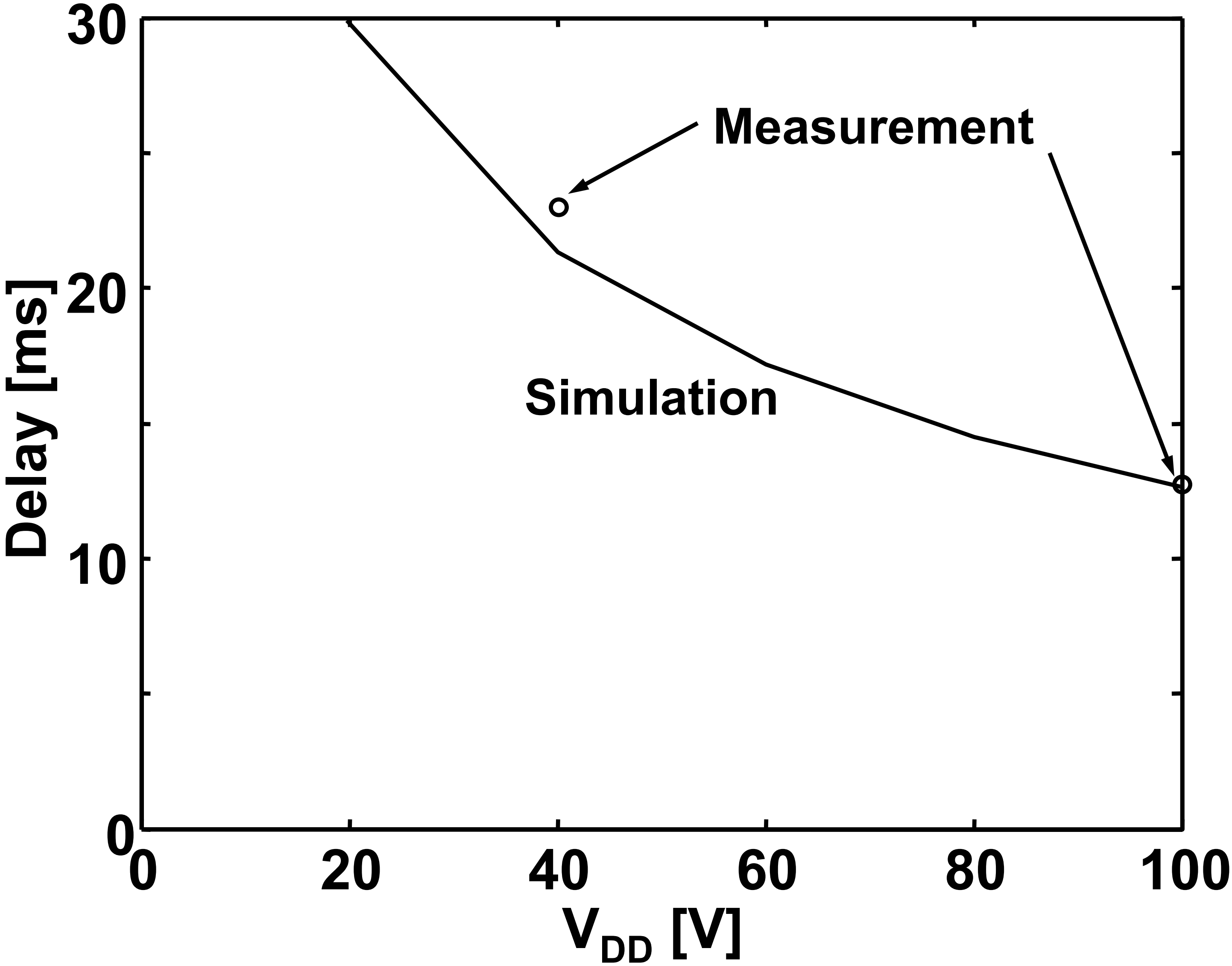

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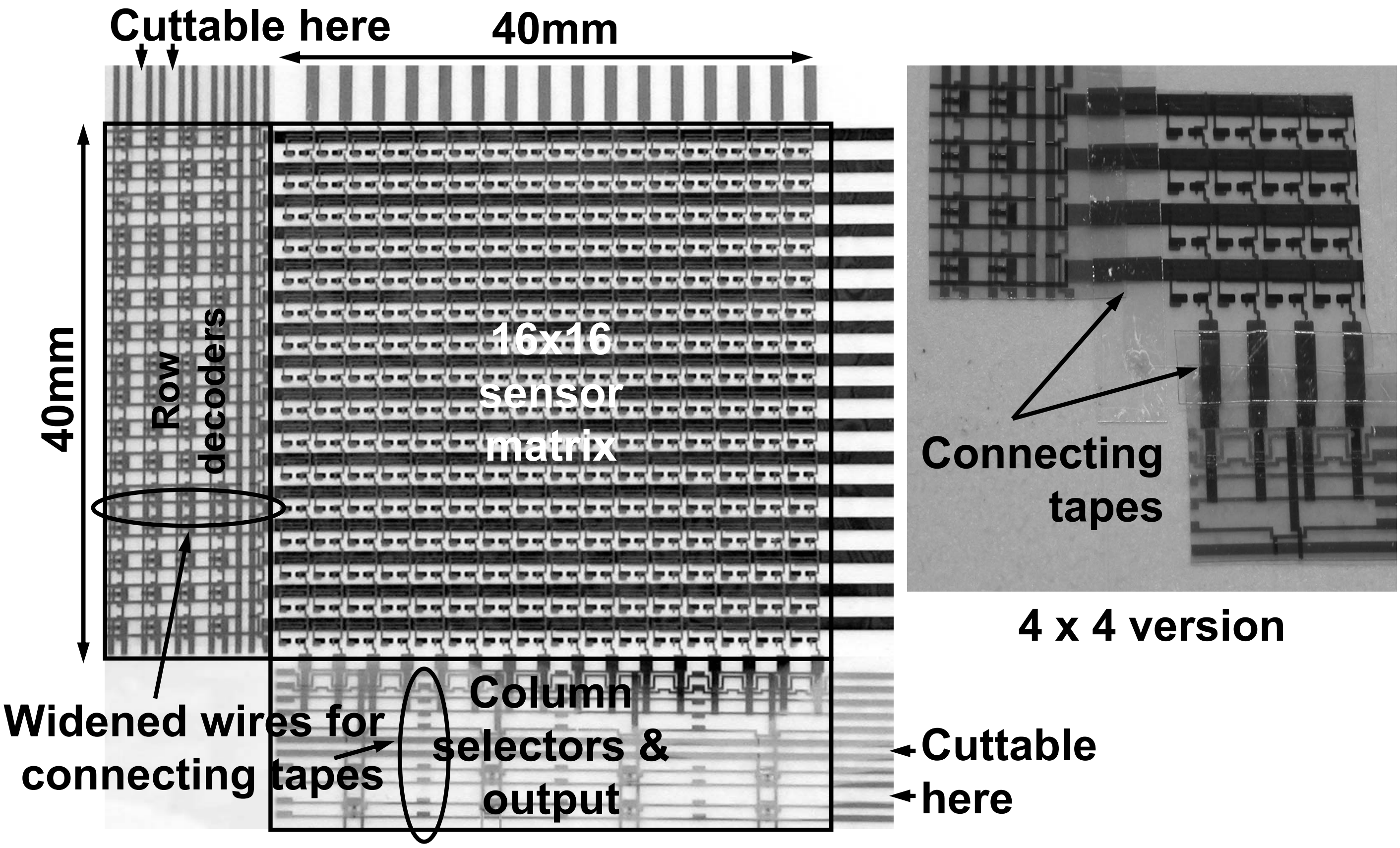

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