Double-Gate Organic Micro-Electro-Mechanical Relay for Ultralow-Power Flexible Large-Area Electronics

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Organic thin film transistors (OTFTs) have been researched over the past decades to enable flexible large-area electronics [1]. Due to the organic materials (e.g., conjugated polymers and small-molecule materials) being employed as the active semiconductor layer however, OTFTs developed to date are subject to the following limitations: Firstly, relatively low field-effect carrier mobility of the active layer material (well below 10 $cm^2V^{-1}s^{-1}$) requires a rather large supply voltage (typically > 10 V) for a reasonable on/off current ratio (> 10^5); Secondly, relatively poor semiconductor/dielectric interface induces fairly large off-state leakage current (I_{OFF}) [2]. Large I_{OFF}, coupled with such a large V_{DD}, would lead to large amounts of static and dynamic power consumption. To overcome the limitations and hence enable ultralow-power flexible large-area electronics, we propose a seemingly-different organic micro-electro-mechanical (MEM) relay as a potential alternative to conventional OTFTs since its unique switching characteristics such as zero I_{OFF} and abrupt on/off switching can provide for zero static power consumption and potentially very-low dynamic power consumption.

Fig. 1 shows an isometric view, cross-sectional views, scanning electron micrographs (SEMs), and design parameters of a polymeric MEM relay of this work. The relay is an eight-terminal device, which has two gate electrodes (under the movable structure), two bodies, and two pairs of source/drain (S/D). The operating principle is the same as that for the relay designs in [3-4]: Briefly, the voltage applied between the gates and bodies (V_{GB}) determines the on- or off-states of the relay. When $V_{GB} \geq V_{PI}$ (pull-in voltage), the relay turns on, and current flows between S/D. When $V_{GB} < V_{RL}$ (release voltage), the relay turns off. **Fig. 2(a)** shows near-zero I_{OFF} (~10 fA), abrupt on/off switching, relatively high I_{ON}/I_{OFF} ratio (~10^7), and V_{PI} and V_{RL} that are tunable with the body bias. **Fig. 2(b)** shows that stable Ohmic contacts are formed between the channel and S/D in the on-state and that I_{DS} increases with increasing gate overdrives (V_{GB}-V_{PI}). **Fig. 2(c)** shows that V_{PI} for the case where input voltages are applied to both of the two gates (i.e., "double-gate" operation) is smaller than that for the two cases where inputs are applied to either one of the gates ("single-gate" operation). V_{PI} for the single-gate operations (with input combinations—either [1 0] or [0 1]) are different from each other due to positive strain gradient within the movable structure, i.e., the actuation gap (g_o) near the center of the movable structure is slightly smaller (by ~25 nm) than that at the edge. Measured timing diagrams (in **Fig. 2(d)**) shows that a single double-gate relay can perform either two-input AND or OR functions via adjusting the body bias.

[1] K. Fukuda *et al.*, *Sci. Rep.*, vol. 4, pp. 3947, 2014.
[2] C. D. Dimitrakopoulos *et al.*, *Adv. Mater.*, vol. 14, pp. 99–117, 2002.
[3] J. Jeon *et al.*, *Electron Device Lett.*, vol. 33, pp. 281–283, 2012.
[4] Y. Pan *et al.*, *Trans. Electron Devices*, vol. 63, pp. 832–840, 2016.

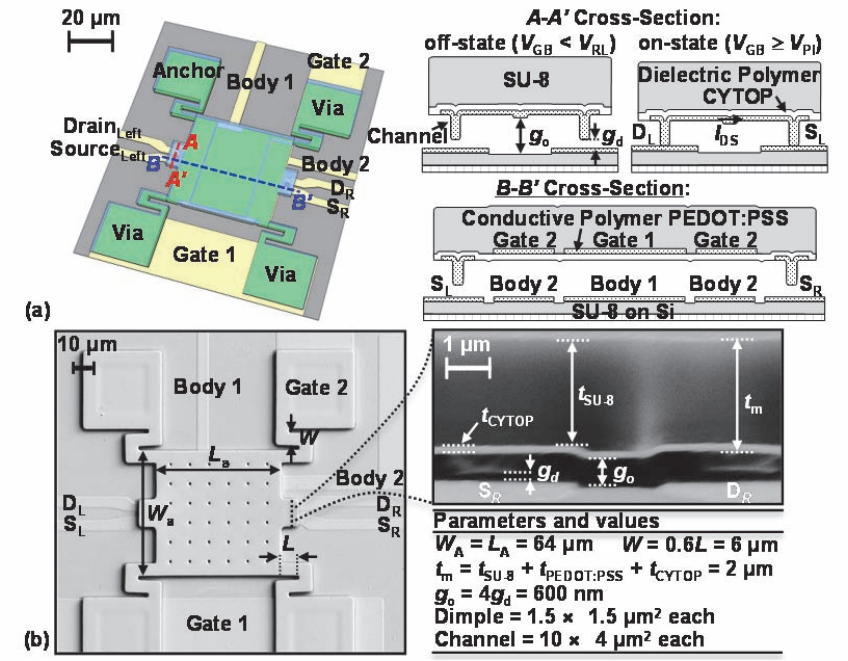

Fig. 1: (a) Isometric schematic and cross-sectional views; (b) SEMs and design parameters.

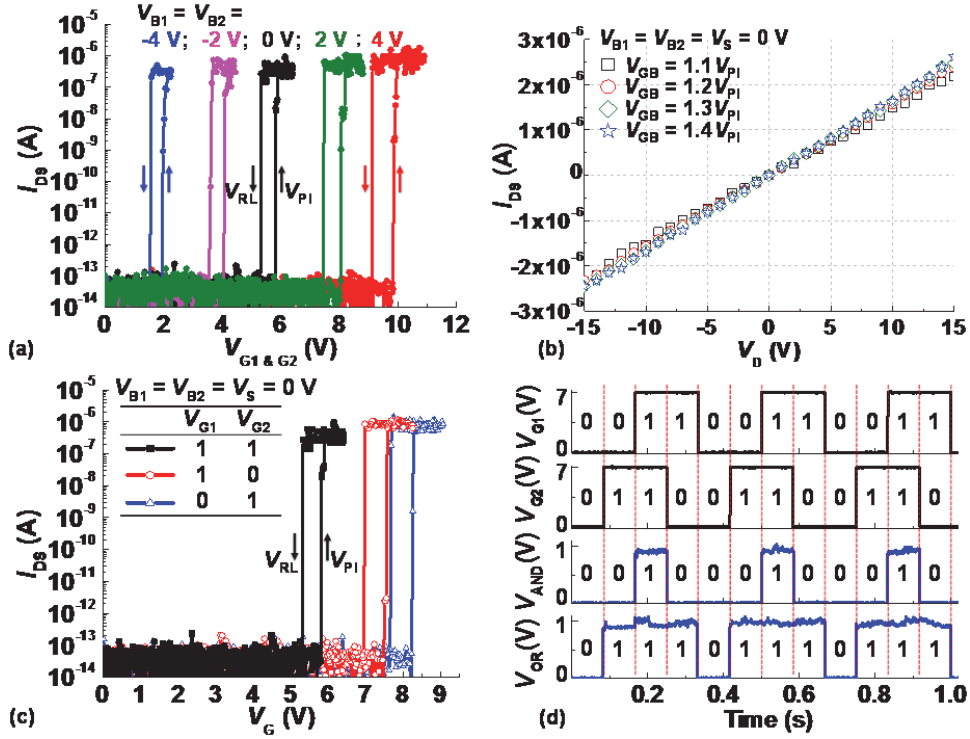

Fig. 2: (a) Measured I_{DS}–V_G for various body bias voltages. $V_D = 1.1V_{PI}$. $V_S = 0$ V; (b) Measured I_{DS}–V_D for different gate overdrive voltages. $V_G = V_{G1} = V_{G2}$; (c) Measured I_{DS}–V_G for different input voltage combinations. "1" ≡ V_G. $V_D = 1.1V_{PI}$; (d) Measured timing diagrams for AND and OR gates. $V_B = 0$ V for AND, $V_B = -2$ V for OR, $V_D = 7$ V and $V_S = 0$ V.