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Rubbery logic gates

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HIGHLIGHTS

- Digital logic operators based on dielectric elastomer technology are demonstrated.
- All 7 basic Boolean logic gates are presented.
- The gates operate at high voltage.
- The gating mechanism relies on mechanical strain rather than standard electronics.
- Only soft polymer and carbon materials are needed.

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ABSTRACT

Dielectric elastomer actuators (DEAs) that possess muscle-like characteristics have received a lot of attention in areas like soft robotics. Traditionally, electronic control for dielectric elastomer (DE) artificial muscles was achieved with rigid external circuitry. Recently, however, a flexible piezoresistive electrode, the dielectric elastomer switch (DES), was introduced that can operate high voltage DEA switching and control. It has been demonstrated that DESs can control charge in high voltage analogue and digital circuitry. In this contribution, we demonstrate high voltage operation of the seven basic Boolean logic gates using mechanosensitive DESs. Logic elements made with DESs may provide signal processing capabilities in DE artificial muscles.

1. Introduction

Logic devices typically rely on electronics for the gating mechanism. For instance, common integrated-circuit NAND gates consist of multiple MOSFETs or several bipolar transistors, diodes, and resistors [1,2]. These components are mounted on a rigid board. Here we present a means for logic gating that is materially softer than the elements of a printed circuit board and that relies on mechanical strain. The technology is based on dielectric elastomer actuators (DEAs) coupled to piezoresistive-charge gates.

A DEA is formed from a dielectric elastomer (DE) membrane, a type of electroactive polymer (EAP), sandwiched between two compliant electrodes. Actuation occurs when voltage is applied to the electrodes, generating electrostatic forces known as Maxwell pressure [3–5]. The resultant deformation in the DE membrane is a coupled compression in thickness and expansion in planar area. The elasticity of the membrane allows it to revert to its original dimensions when the voltage is removed. Voltage-induced deformation of DE materials has been continually increasing since early works demonstrated over 100% areal strains, with the record currently at 2200% areal strain [4,6–8].

DEAs have characteristics comparable to those of biological muscles, including strain-actuation, pressure, power density, and work-per-cycle performance [9]. These properties, particularly the ability to generate large strains, make DEAs a favored actuator technology for use as artificial muscles [10,11].

In 2010, O'Brien et al. demonstrated the dielectric elastomer switch (DES) [12], which is a flexible piezoresistive electrode that can be coupled with DEAs to control charge over the actuators. DESs are composed of conductive particles dispersed in a non-conductive matrix [12,13], therefore DESs function via the percolation effect [14,15]. When compressed beyond the percolation threshold, a DES will undergo orders of magnitude change in resistance [12,16]. Thus, the in-plane expansion of a DEA can be exploited to exert force over a switch and the changing resistance of the switch can be used to control the charge over a DEA.

Automatic charge control of DE artificial muscles using DESs has been demonstrated in oscillators [17,13], a dielectric elastomer

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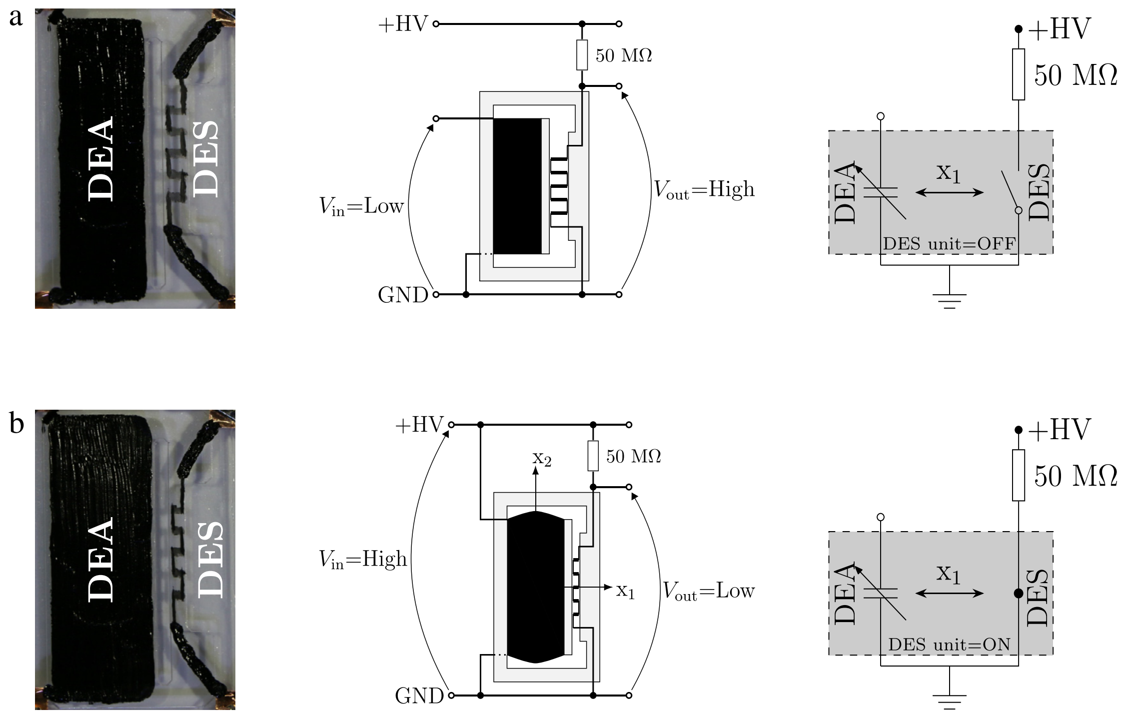

Fig. 1. Representative images (left), schematics (middle), and equivalent circuit diagrams (right) of a single DES unit: (a) off state and (b) on state. In the off, or relaxed, state, the input voltage is zero so that the DE actuator and switch do not experience any mechanical strain beyond their pre-stretched state. In the on, or actuated, state, the input voltage is high so that the DEA expands in area, indicated by arrows x_1 and x_2, and the DES is compressed. Since DEAs are essentially flexible capacitors formed from pliable dielectrics and electrodes, they are represented by the symbol for a variable capacitor in the circuit diagrams.

generator [18], and a self-commutating rotory motor [19]. DESs were also used in the production of a Turing machine [20] that performed calculations based on digital logic. DESs directly couple mechanics with digital logic [12], which is a key distinction of DESs relative to other flexible electrodes [21–23]. These developments support further exploration of logic devices using DE artificial muscles and switches.

In this contribution, we demonstrate the construction and operation of soft digital logic elements, the seven basic Boolean logic gates, using high voltage electromechanical dielectric elastomer switching. The seven basic Boolean logic gates include NOT (inverter), NAND, AND, NOR, OR, exclusive-NOR (XNOR), and exclusive-OR (XOR) gates [1,2,24]. The truth tables for these logic operators having two inputs are shown in Table 1. The inverter has only one input and one output: when the input is logical 1 the output is logical 0, and when the input is logical 0 the output is logical 1 [1,2,24].

Boolean logic gates are building blocks for combinatorial logic circuits. Thus, combinations of gate structures can create various logical functions, which can be fitted to a broad range of applications. Soft logic gates made up of pliable materials may be integrated with artificial muscle devices to provide local signal processing and reduce the need for bulky external circuitry.

2. Materials and methods

DEAs are 362% equibiaxially pre-strained VHB 4905 (3M, USA) and electrodes are painted-on Nyogel 756G (Nye Lubricants, USA). The switching compound is an approximately 5:1 by weight mixture of non-conductive Molykote 44 Medium grease to conductive Cabot Vulcan XC72 carbon black. Switches were transfer printed onto DE membranes using a polydimethylsiloxane (PDMS) stamp. Membranes were mounted on 3 mm-thick transparent acrylic frames[1] that had 60 × 35 mm windows, and strips of PMMA (3 mm wide) were placed between the actuator and switch to promote a uniform deformation of the switch. Metal screws and copper tape on the frames served as electrical connections to a high voltage source.

Table 1
Truth tables for 2-input Boolean logic gates [1,2,24].

Inputs		Outputs					
V 1	V 2	NAND	AND	NOR	OR	XNOR	XOR
0	0	1	0	1	0	1	0
0	1	1	0	0	1	0	1
1	0	1	0	0	1	0	1
1	1	0	1	0	1	1	0

A structural DES unit is demonstrated in both relaxed and actuated states in Fig. 1. Switches connected to a high voltage terminal were placed in series with a resistor, which inhibited electrical breakdown of the switches and served as a pull-up resistor [2] for the logic gates. The resistor value, 50 MΩ, was large enough to prevent spark erosion of the switches but not too large to cause an excessive drop of voltage across itself when the gate was in a state of sourcing current, i.e. had a high (logical 1) output.

2.1. Gate designs

The NOT gate (inverter) design, shown in Fig. 2, is comprised of a single DES unit. A high voltage input (logical 1) induces elongation in the actuator which compresses the switch and decreases its resistance so that the voltage output becomes low (logical 0). Inversely, a low voltage input (logical 0) will not expand the actuator and the switch will remain non-conductive, thus the voltage output will be high (logical 1).

The designs for 2-input gates are shown in Fig. 3. It is noteworthy that other structural designs are possible. In particular, the universal gates NAND and NOR can independently form the other gates. For example, the NAND gate can behave as an inverter either by using the same signal for both inputs or by having only one

1 poly(methyl methacrylate) (PMMA), common name: Perspex.