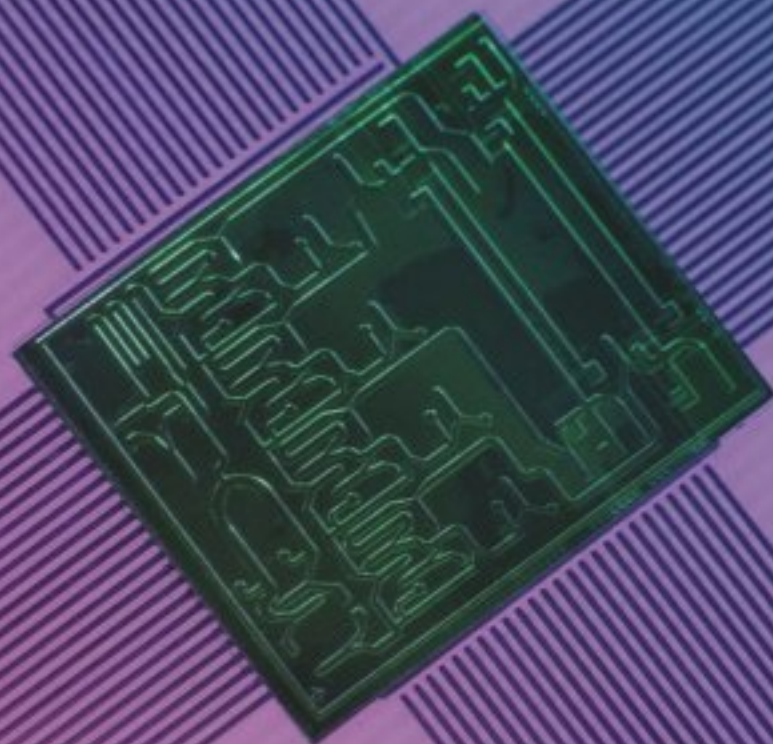


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10

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Contents

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Research Articles

Shock Resistance of MEMS Capacitive Accelerometers <i>Yongkang Tao, Yunfeng Liu, and Jingxin Dong</i>	1
Research on Nonlinear Vibration in Micro-machined Resonant Accelerometer <i>Shuming Zhao, Yunfeng Liu, Fan Wang, Jingxin Dong</i>	14
Reversible and Irreversible Temperature-induced Changes in Exchange-biased Planar Hall Effect Bridge (PHEB) Magnetic Field Sensors <i>G. Rizzi, N. C. Lundtoft, F. W. Østerberg, M. F. Hansen</i>	22
Synthesis and Characterization of Nickel Ferrite (NiFe₂O₄) Nanoparticles with Silver Addition for H₂S Gas Detection <i>N. Domínguez-Ruiz, P. E. García-Casilla, J. F. Hernández-Paz, R. C. Ambrosio-Lázaro, M. Ramos-Murillo, H. Camacho-Montes, C. A. Rodríguez González</i>	35
Electron-Relay Supercapacitor Mimics Electrophorus Electricus's Reversible Membrane Potential for a High Rate Discharge Pulse <i>Ellen T. Chen and Christelle Ngatchou</i>	42
Ultralow Detection of Bio-markers Using Gold Nanoshells <i>Dhruvinkumar Patel, Xinghua Sun, Guandong Zhang, Robert S. Keynton, Andre M. Gobin</i>	49
Evaluation of Anchoring Materials for Ultra-Sensitive Biosensors Modified with Au Nanoparticles and Enzymes <i>Solomon W. Leung, David Assan and James C. K. Lai</i>	59

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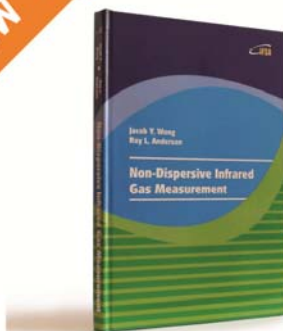
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Electron-Relay Supercapacitor Mimics *Electrophorus Electricus*'s Reversible Membrane Potential for a High Rate Discharge Pulse

* Ellen T. CHEN and Christelle NGATCHOU

Advanced Biomimetic Sensors, Inc. 20271 Goldenrod Lane #2064
Germantown, MD 20876, USA

* Tel.: 301-528-2273

E-mail: Ellenchen@nanobiomimeticsensors.com

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Abstract: *Electrophorus Electricus* (EE) is known to discharge electric voltage through multiple organs based on Reversible Membrane Potential (RMP). We report a new type of supercapacitor for mimicking the EE's RMP based on an Electron-Relay Nano-Biomimetic Membrane Electrode Assembling (ERNBMEA) and an asymmetric membrane design with features free from ion channeling effect and a negligible double layer potential effect. The results shown the newly developed device can fire high rate electric spikes at both ends of the anode and cathode with a firing rate of 2-fold higher compared with the EE's 3.75 V/s. The capacitance of the 0.2 cm³ biomimetic EE increased linearly from 0.25 to 13,240 $\mu\text{F}/\text{cm}^2$ over 0.015 to 1000 Hz range. At 120 Hz, the high storage capacitance is 5,140 $\mu\text{F}/\text{cm}^2$ that is an order of magnitude higher over the reported double-layer capacitor.

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Keywords: Electron-relay supercapacitor, Reversible membrane potential, Nano-biomimetic *Electrophorus Electricus*'s device, High rate electric firing pulse, Asymmetric design.

1. Introduction

Electrophorus Electricus is known to its discharge electric voltage pulses through multiple organs based on Reversible Membrane Potential (RMP) [1-2]. Piccolino et al summarized John Wash's studies in electric fish [3]. Nowadays, researchers are increasingly interested in study of the electric fish and seek a nature inspired way to develop more efficient energy converting devices by developing

artificial electric fishes [4-6]. The article may mimic the biological cell's ion channel functions [4], or mimic electric fish's electroreceptive capabilities to find a target without seeing at the deep underwater [5]. There is an important area of multiple-organ discharge mimicking the EE fish that has not been pursued. The goal of this research is to develop an Electron-Relay (ER) prototype supercapacitor that mimics *Electrophorus Electricus*'s reversible membrane potential for multiple-organ discharge under Double-Layer Potential (DLP) negligible, oxygen-independent and electrolyte-free conditions. The rationale of these settled conditions are based on the needs of many patients who suffer from unbalanced axon action/resting potential due to dysfunction of Ion-channel or ATP pump dysfunction, such as Trauma Brain Injury (TBI), various cancer diseases and chronic illness. We will design an energy platform device without electrolyte-dependence and with minimum DLP that will simplify and eliminate the error source contributions from the device membrane. Air-dependent is common for most nature enzymes; however, it can create a problem of CO₂ emission in a closed compartment of underwater vehicles if a nature enzyme used as the source of an energy device. Therefore, using an air-independent nanostructure biomimetic membrane electrode assembling will offer advantages for accomplishing the goal of this study.

2. Experimental

2.1. Asymmetric Design of the Supercapacitor

Supercapacitors have two categories by energy storage mechanism: electrochemical double-layer capacitors (DLCs) and redox supercapacitors [7-9]. An approach to overcome the low Gravimetric Energy Density (GED) of the DLS supercapacitor is to use an asymmetric design: 1. the positive electrode has a low degree of polarization, and 2. the negative electrode has a high degree of polarizability in an attempt to enlarge the window of the difference of the potential change during charge and discharge [9]. After E. Chen's group developed an electrolyte-free and oxygen-independent battery/fuel cell device [10-13], the GED and the power density performances were superior. However, we now have an asymmetric design for the Biomimetic electron-relay supercapacitor in order to mimic EE's reversible multiple-organ discharge as shown in Fig. 1.

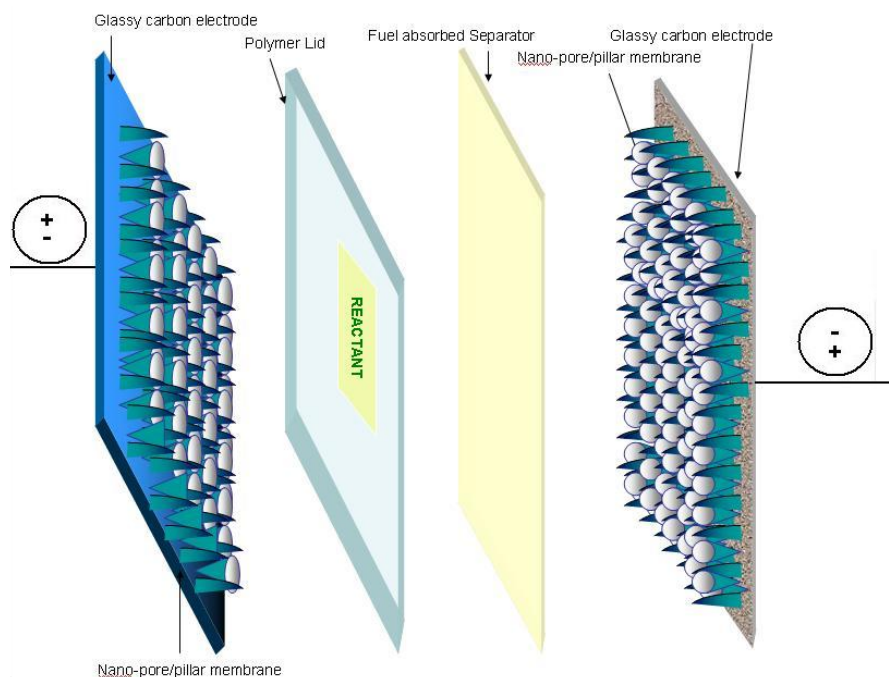


Fig. 1. Illustrates the asymmetric design of the electron-relay nanobiomimetic supercapacitor.

One electrode with GC/nanopore/pillar structured Membrane Electrode Assembling (MEA), and the other MEA was with an embedded “reactant” flat surface structure with a membrane thickness 48 nm [11]. An insulator was placed between the two MEAs and absorbed with 1M methanol under electrolyte-free condition. The current collectors were attached at each end. Fabrication and characterization using Atomic Force Microscope (AFM) for the two MEA membranes were described elsewhere [11]. The one MEA with embedded reactant o-nitrophenyl acetate (o-NPA) was called as an “Electric-Dam” configuration, and another MEA without embedding of o-NPA was called as an “Electric-Well-Pillar” configuration according to their Atomic Force Microscopic images [11].

3. Results and Discussions

3.1. The Electron-Relay Biomimetic Prototype Supercapacitor

As shown in Fig. 1 for the asymmetric design of the supercapacitor, the electron-relay with and without a lid of embedded “reactant” created a dynamic window of potential change, not only it enhanced the high potential discharge, but also created a flexible and reversible “multiple-location” discharge possibility, that is to mimic the EE’s multiple-organ discharge as shown in Fig. 2.



Fig. 2. Illustrates the EE’s multiple-organ discharges at Sach and Hunter organs.

3.2. Double-layer Potential (DLP) Effect

DLP effect is the base for most supercapacitors, however, since we created the E-R system for the energy storage and tried to eliminate the DLP effect and create a unique “supercapacitor” that does not rely on electrolyte and is not dependant on the DLP. Fig. 3 confirmed our approach that the supercapacitor has negligible DLP effect and one single cell prototype is an ideal nonpolarizable device as for curve c [14], and when switched the two electrodes are an ideal polarizable device. Curve d shows the half cell behavior acts like a switchable semiconductor at zero and ± 0.1 A that indicates the asymmetric design reached desired goal under the electrolyte-free, air-independent and DLP negligible conditions. This design paved a foundation for multiple-location discharge with a controllable flexibility and intensity.

3.3. High Rate Discharge Pulse

3.3.1. “Multiple-Organ” Discharge

Fig. 4 illustrates the discharge and charge curves from a single 0.5 cm^2 prototype device, A and B curves indicate the “multiple-organ” charge and discharge behavior; Fig. 5 illustrates the same behavior shown for the 1 cm^2 single prototype device in discharge with a switchable two ends discharge.

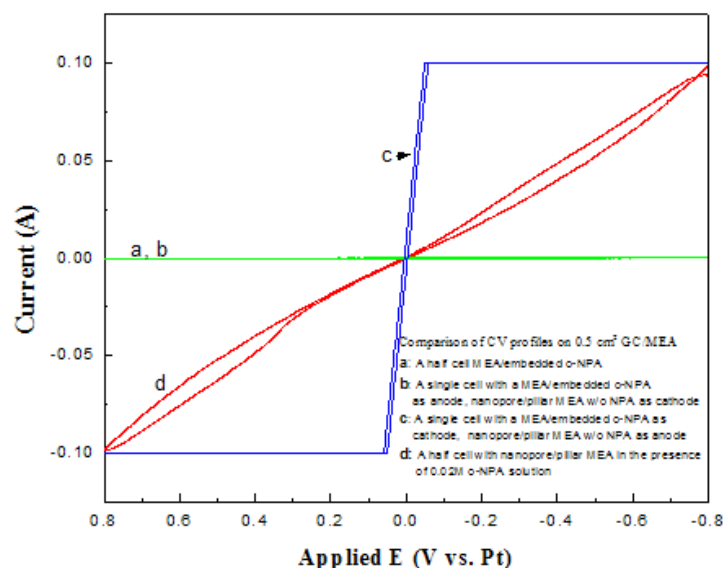


Fig. 3. Plots of Cyclic Voltammograms of the Biomimetic EE device.

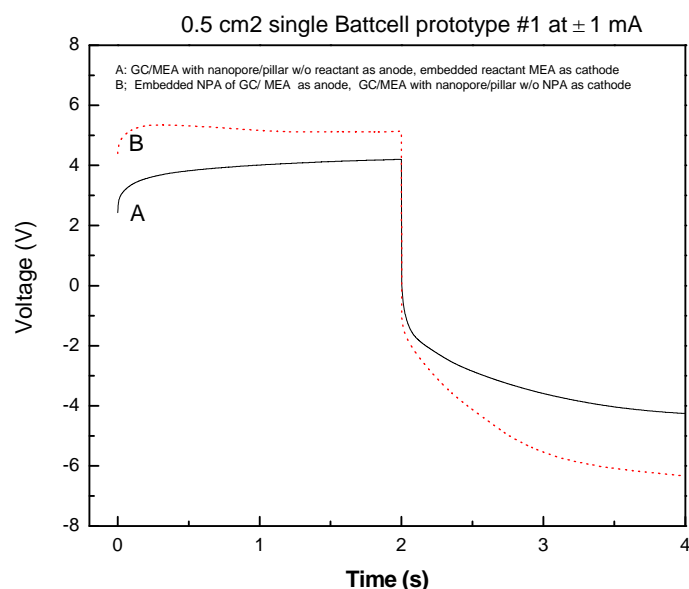


Fig. 4. Illustrates the single 0.5 cm^2 prototype device reversible EE membrane charge and discharge behavior based on the “Electric-Dam” and the “Electric-Well-Pillar” configurations as shown in Fig. 1.

3.3.2. High Rate Discharge Pulse

The high electric spikes at either end of anode and cathode have a firing rate of 2-fold higher compared with the EE's 3.75 V/s as seen in Fig. 5 using single step chronopotentiometry method. Fig. 6 illustrates the high rate discharge pulse of 10 V/s at -8 mA . The power and energy density for a single 0.2 cm^3 cell are several order of magnitudes higher than the EE's single electrocyte of 0.03 W/kg and 0.03 Whr/kg , respectively.

3.4. Supercapacitor

The charge/discharge profiles from the 0.2 cm^3 prototype supercapacitor is shown in Fig. 7 at 1 mA over the band width from 0.015 Hz to 1000 Hz using the *Double Step Chronopotentiometry* (DSCPO)

method. Fig. 8 is the plot of capacitance vs. frequency that indicates at 120 Hz, the high storage capacity is $5,140 \mu\text{F}/\text{cm}^2$ over the reported data of $175 \mu\text{F}/\text{cm}^2$ of double-layer capacitor [7]. The capacitance of the 0.2 cm^3 biomimetic EE increased linearly from 0.25 to $13,240 \mu\text{F}/\text{cm}^2$ over a 0.015 to 1000 Hz window.

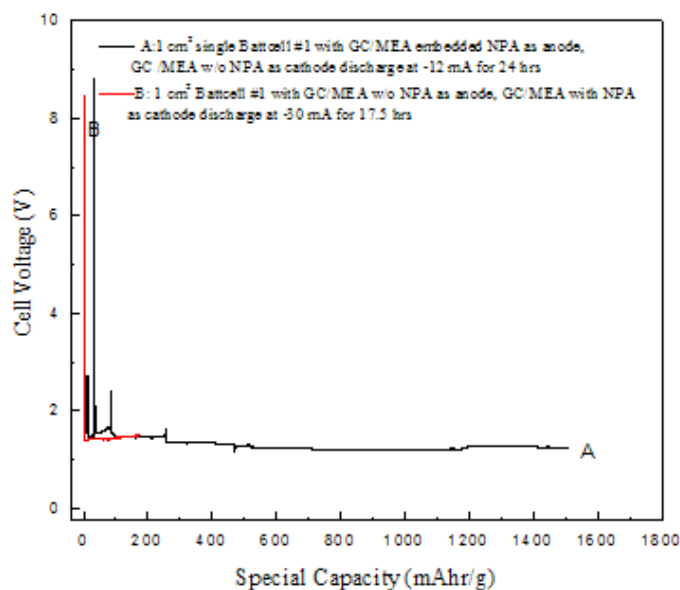


Fig. 5. Illustrates a single 1 cm^2 prototype RM discharge.

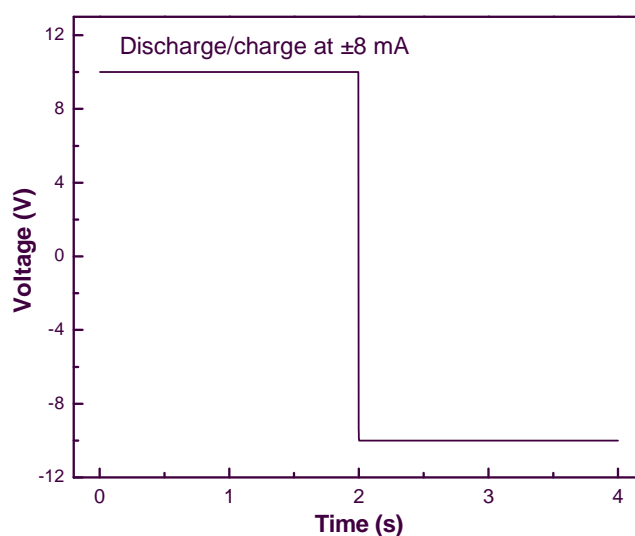


Fig. 6. Illustrates a single 1 cm^2 prototype at a high rate pulse charge/discharge at $\pm 8 \text{ mA}$.

4. Conclusion

Results presented here in Table 1 are for *Nano-biomimetic supercapacitor* (NBMSCAP) compared with the EE's discharge performance at both ends with RMP functions. The results shown the newly developed device can fire high rate electric spikes at both ends of the anode and cathode with a firing rate more than 2-fold higher compared with the EE's 3.75 V/s . The capacitance of the 0.2 cm^3 biomimetic EE increased linearly from 0.25 to $13,240 \mu\text{F}/\text{cm}^2$ over 0.015 to 1000 Hz range. At 120 Hz, the high storage capacitance is $5,140 \mu\text{F}/\text{cm}^2$ that is an order of magnitude higher over the reported double-layer capacitor.

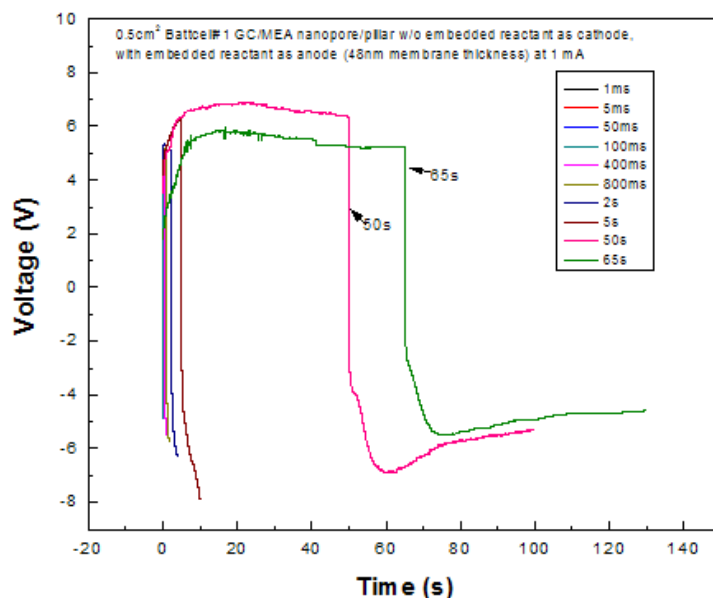


Fig. 7. Illustrates the 0.2 cm³ supercapacitor charge/discharge profiles over the band width from 0.015 Hz to 1000 Hz at 10 increment levels.

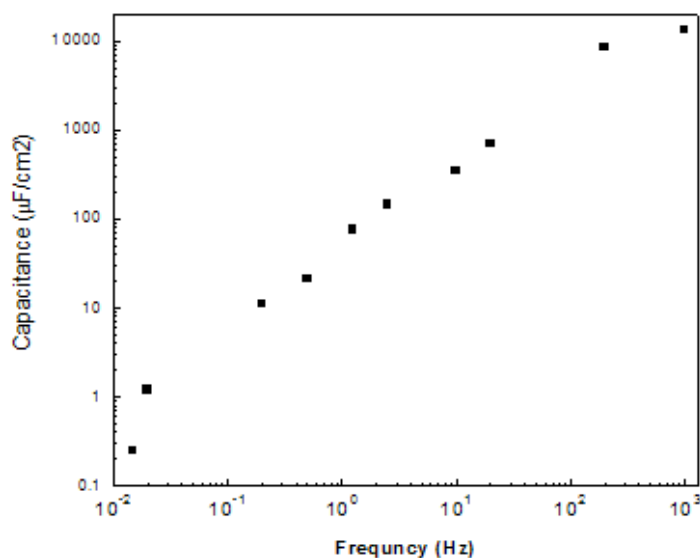


Fig. 8. Plot of the capacitance versus frequency (Hz) of the supercapacitor assuming a series RC circuit model.

Table 1. Comparison of performance between NBMSCAP and the *Electrophorus electricus*.

Name	Discharge rate, (V/single cell/s.)		Discharge location		O ₂ Food CO ₂
	(head)	(tail)	(head)	(tail)	
NBMSCAP ¹	4V/s	10 V/s	240 V (60 cell)	1000 V (100 cell)	No No No
<i>Electrophorus electricus</i> (5000 electrocytes)	-	² 3.75 V/s	10 V ³	500 V ⁴	Y Y Y

¹ Refers to the single 0.5 cm² prototype device consists of a GC/MEA (48 nm membrane) embedded with o-NPA as anode and another GC/MEA without embedded o-NPA, with nanopore/pillar structure, as cathode, separated by an insulator, and with Pt as current collector. ² <http://en.wikipedia.org>. ³⁻⁴ Based on 5000 electrocytes at citation 2. The EE discharge mechanisms were explained in Simon, Stéphanie; Massoulié, J: *Cloning and Expression of Acetylcholinesterase from Electrophorus*, Journal of Biological Chemistry 272 (52): 33045–33055, 1997.

The new approaches to mimic EE's RMP and optimally used for "Multiple-Organ" discharge with a sharp electric firing rate may find applications for further improving energy storage devices.

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Sergey Y. Yurish



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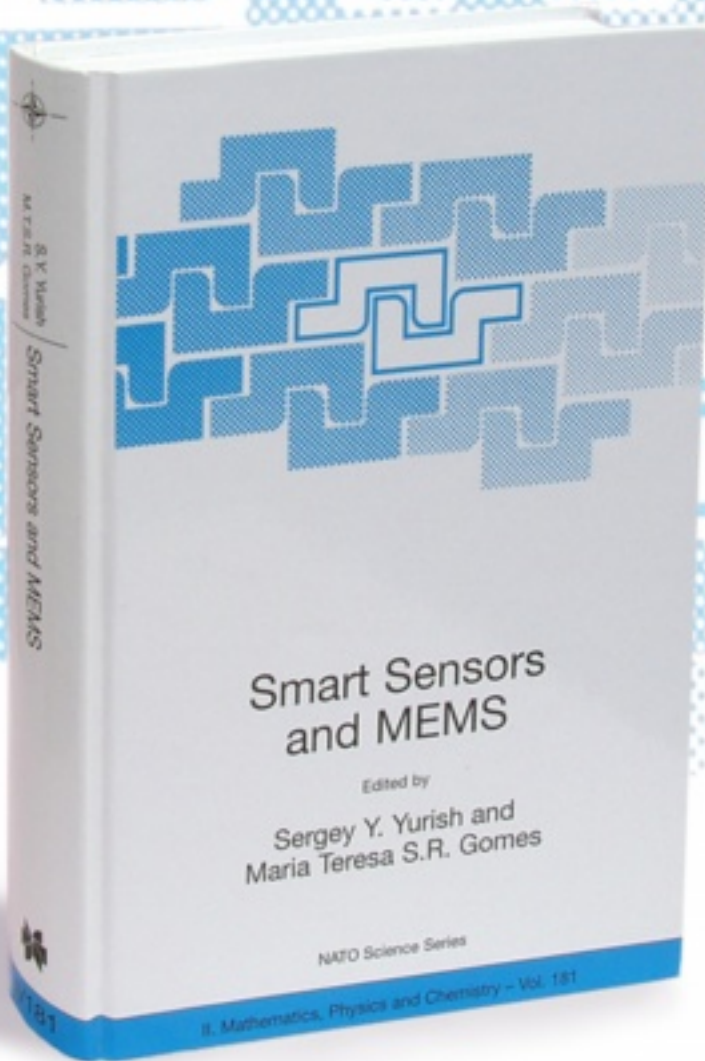
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