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Constitutive models of artificial muscles: a review

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Schematics of a dielectric elastomer (DE)

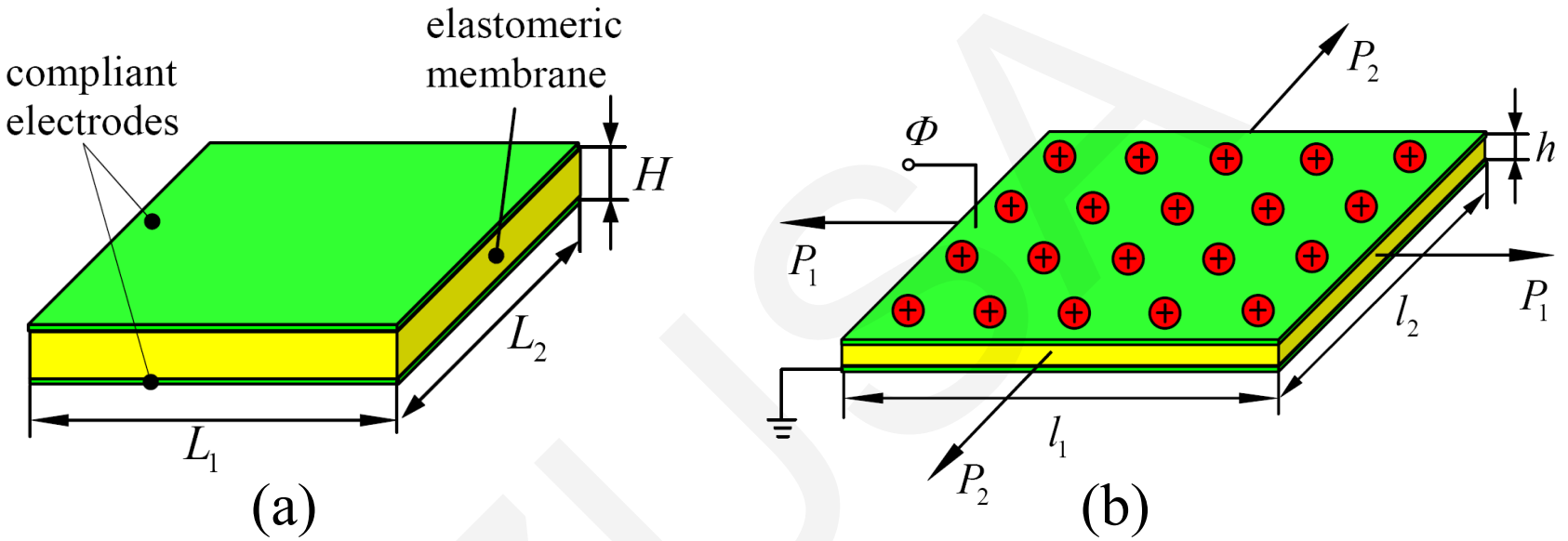
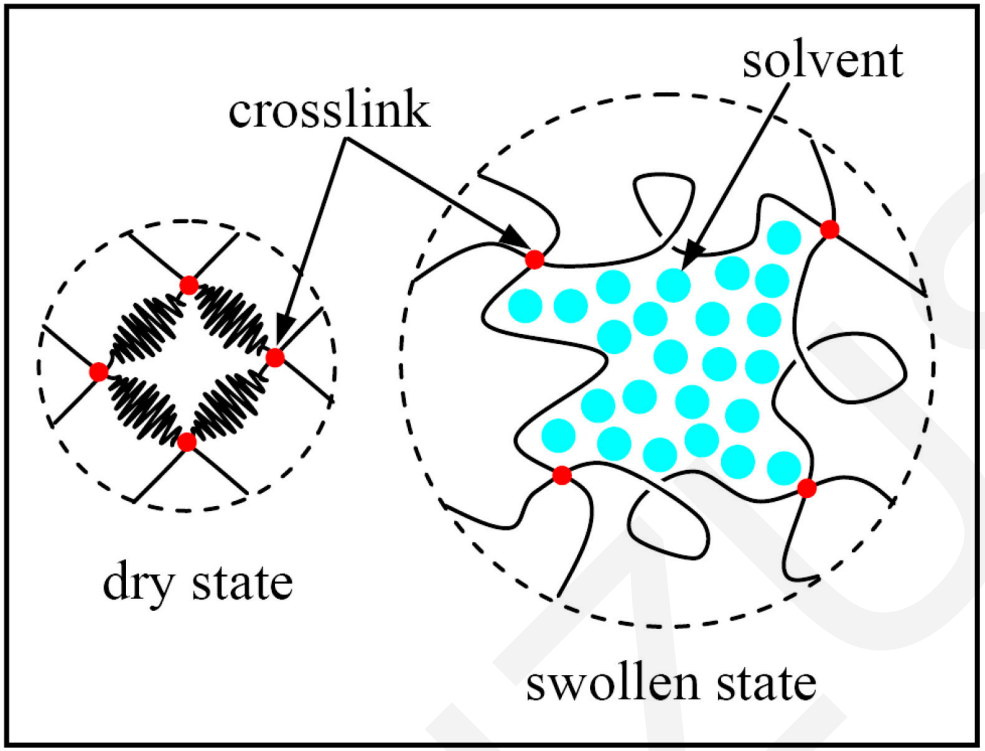


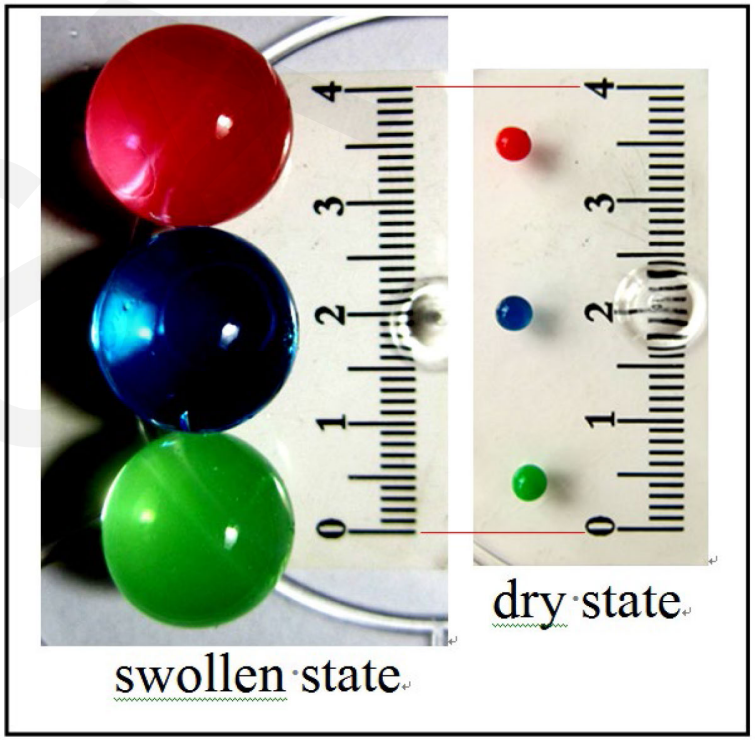
Fig. 1 Schematics of a dielectric elastomer in different states

(a) reference state: an elastomeric membrane of sides L_1 and L_2 and thickness H is sandwiched between two compliant electrodes. (b) deformed state: the dielectric elastomer deforms to sides l_1 and l_2 and thickness h when subjected to the mechanical loadings P_1 and P_2 and a high voltage Φ.

Schematics of a responsive gel (RG)



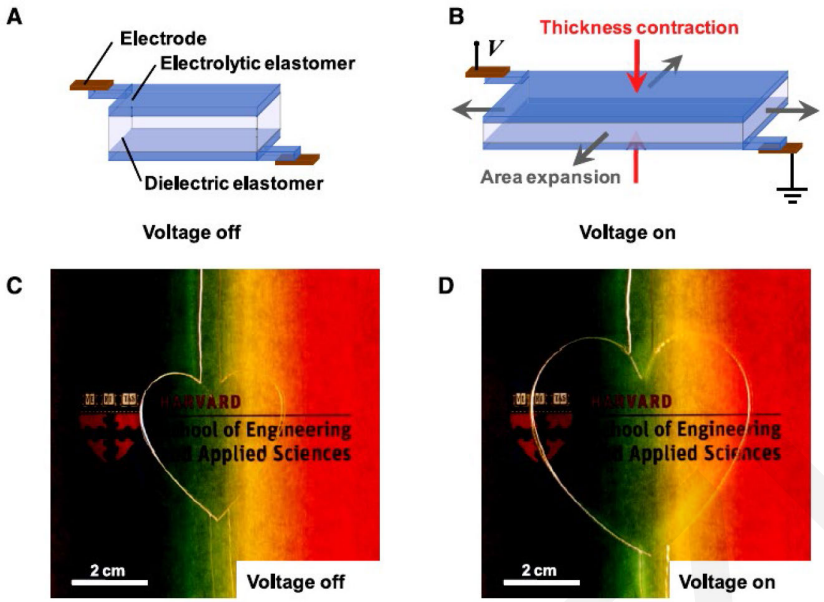
(a)



(b)

Fig. 2 Schematics (a) and photos (b) of a responsive gel

Representative applications of DE



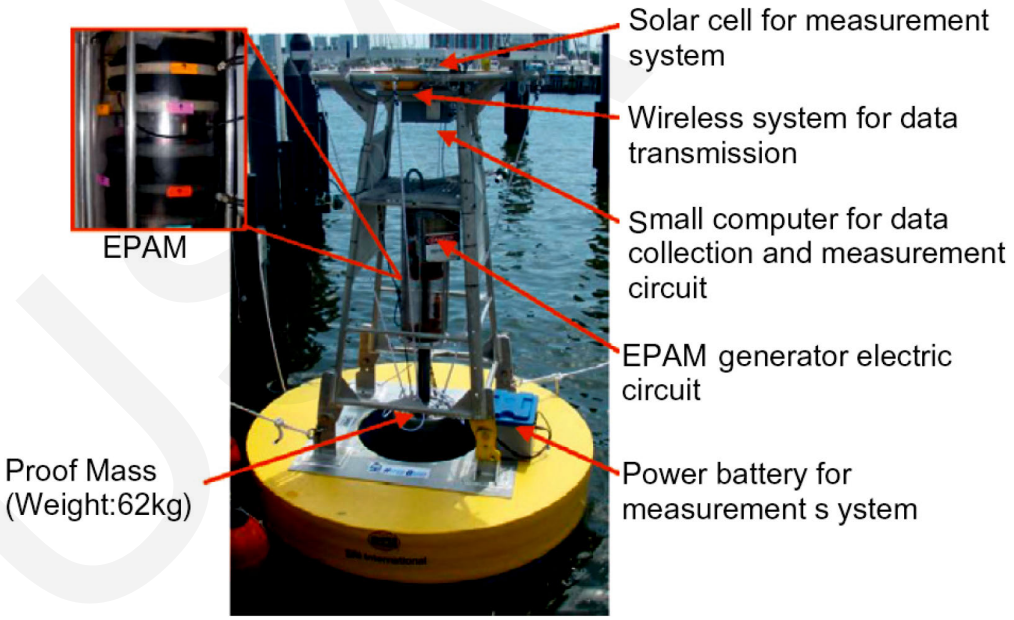


Fig. 3 DE transparent actuator

C. Keplinger et al., Science, 2013, 341: 984-987.

Fig. 4 DE energy harvester

Chiba S. et al., Applied Energy, 2013, 104: 497-502.

Representative applications of RG

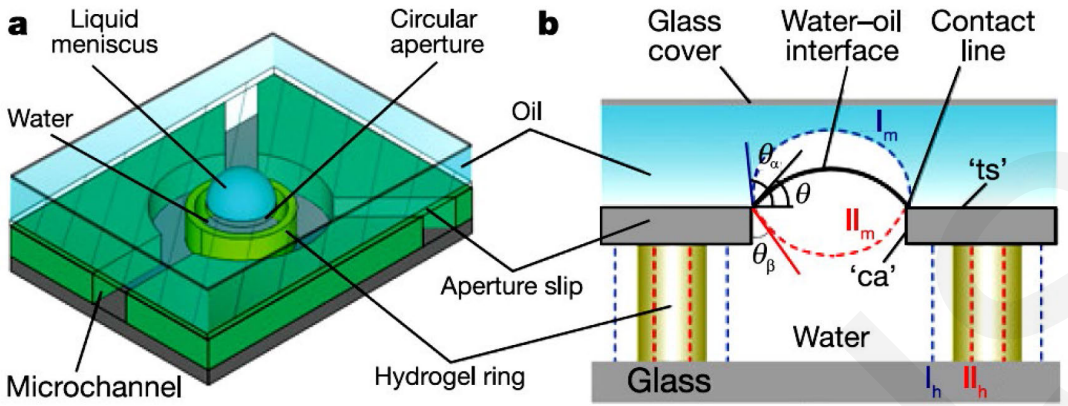


Fig. 5 microlens

L. Dong et al., Nature, 2006, 442: 551-554.

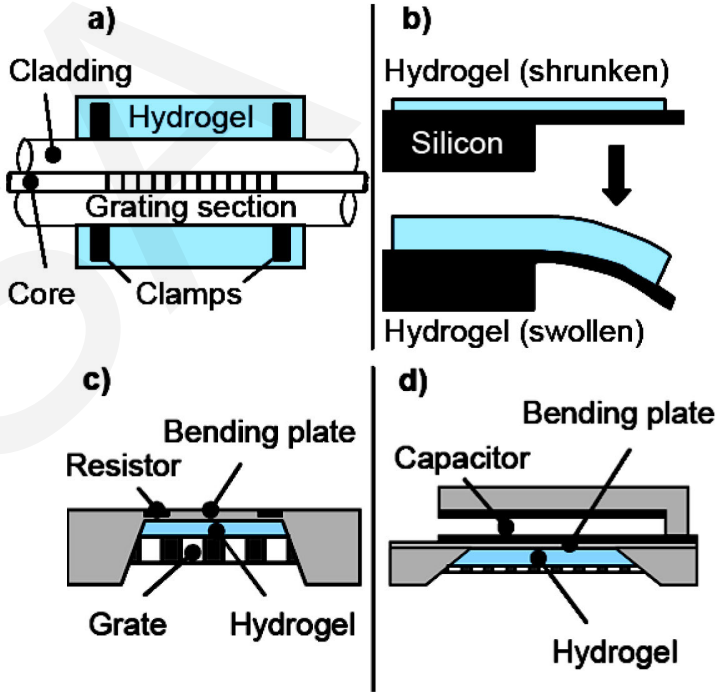


Fig. 6 Hydrogel sensors

A. Richter, et al., Sensors, 2008, 8: 561-581.

Table 1 Some frequently-used stretching energy functions for incompressible dielectric elastomers

Model	Expression of W_s	WLCE	NMP	Parameter	Type
neo-Hookean (Treloar, 1943)	$W_s = \frac{\mu}{2}(I_1 - 3)$	No	1	μ	A
Mooney-Rivlin (Mooney, 1940; Rivlin, 1948)	$W_s = C_1(I_1 - 3) + C_2(I_2 - 3)$	No	2	C_1, C_2	B
Ogden (Ogden, 1972)	$W_s = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}\left(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3\right)$	Yes	$2N$	μ_i, α_i (i=1, 2, …, N)	B
Yeoh (Yeoh, 1990)	$W_s = \sum_{i=1}^{3} C_i (I_1 - 3)^i$	No	3	C_1, C_2, C_3	B
Arruda-Boyce (Arruda and Boyce, 1993)	$W_s = \mu n\left[\frac{\beta_{ch}\lambda_{ch}}{\sqrt{n}} + \ln\left(\frac{\beta_{ch}}{\sinh\beta_{ch}}\right)\right]$, $\lambda_{ch} = \sqrt{\frac{I_1}{3}} = \sqrt{n}\left(\frac{1}{\tanh\beta_{ch}} - \frac{1}{\beta_{ch}}\right)$	Yes	2	μ, n	A
Gent (Gent, 1996)	$W_s = -\frac{\mu}{2} J_{\lim} \ln\left(1 - \frac{I_1 - 3}{J_{\lim}}\right)$	Yes	2	μ, $J_{\lim}$	B

* Note: type A: classic statistical mechanics model; type B: phenomenological model; NMP: number of material parameters; WLCE: with limiting chain extensibility; I_1 and I_2 are the first and second invariants of the right Cauchy-Green deformation tensor

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Conclusions

The constitutive models are an important foundation for predicting and improving the performance of artificial muscles.

Based on equilibrium and non-equilibrium thermodynamics, the constitutive models of dielectric elastomers and responsive gels can be effectively constructed by using free energy functions. In the models presented, the material parameters can be determined by fitting to the experimental data.

The constitutive models of artificial muscles have been widely used in analyzing the electromechanical or chemomechanical behaviors of dielectric elastomer and gel based actuators, sensors, energy harvesters, soft robots and soft tissues, etc.

There are a number of constitutive models for rubber-like materials. It is important to select a suitable model for theoretical analysis of soft materials.