

# Piezoelectric and piezooptic effects in porous silicon

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## ABSTRACT

Although silicon is a simple cubic crystal, it can be induced to have a piezoelectric response, by making pores in it and thus spoiling its symmetry. By etching a silicon wafer into porous material, we found that it responds to voltage applied to it, as well as to light. A porous shallow layer on the surface of the wafer induced bimorph bending roughly proportional to the voltage squared. Illuminating the porous patch caused a similar bending.

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Large efforts are made to produce deformable mirrors and actuators, mostly for adaptive optics. Such a mirror has to be agile enough to correct even the strongest and densest wave front fluctuations, usually a few micrometers in stroke, achieved by few to thousands of actuators<sup>1-3</sup>. In the bimorph deformable mirror a thin piezoelectric actuator stretches or shrinks in area while glued to a thin inert mirror, changing its curvature with the applied voltage<sup>3-5</sup>. Other mirrors employ electrostatic pull and are compatible with micro-electro-mechanical systems (MEMS) manufacturing methods<sup>3</sup>.

Is it possible to achieve a similar effect on less-ordered actuators? We investigated this by applying first voltage and then light to porous silicon (pSi)<sup>6</sup>. At high porosity the residual matter is made of separate islands, and thus its conduction is low. The percolation porosity varies with different raw silicon stoichiometry, orientation, processing procedure and processing chemicals.

We constructed and tested a bimorph device, where part of it was a flat mirror and the other part a flat driving element, modified out of the mirror material itself, thus saving the need for their attachment. The device was a silicon wafer (1" or 2" *n*-type), polished on both sides, whose front (mirror) side was evaporated with a reflective layer and then annealed at 450°C for 30 minutes. A circle on the back side of the wafer (half its diameter) was made porous by etching in HF:ethanol (1:1) solution, with the HF itself dissolved in water (1:1). An initial current of 120-130 mA, (24 mA/cm<sup>2</sup>) was applied to the sample, while being illuminated by a 50W halogen lamp. Etching for 35 minutes set the thickness of the porous layer up to 50 μm, out of 200-400 μm total wafer thickness. The sample was washed a few times by ethanol, then left in ethanol for 30 minutes for final removal of the HF. It was then passivated in oxygen atmosphere for 30 minutes at 450°C. 1 mm electrodes were formed on

the conductive silicon (as ground) and on the pSi, either by attaching thin wires to it directly with a small drop of silver paint, or to gold pads grown on it.

Application of voltage  $V$  between the electrodes and the silicon wafer or illumination of the pSi leads to its deformation. The induced stress causes non-local bending of the wafer, similar to a bimorph mirror. The strain of a plate made of two layers follows the biharmonic equation, which is reduced for a circular boundary to the harmonic (Poisson) equation<sup>4</sup>. A good fit was found to a model of the stress depending mainly on  $V^2$  but also on  $V$ . The reflected wave front excursions  $W(r)$ , equal to twice the strain, are

$$\nabla^2 W(r) = \gamma [dV(r) + mV^2(r)] \quad (1)$$

where  $V(\mathbf{r})$  is the voltage distribution on the electrodes, and the constant  $\gamma$  depends on the thicknesses, Poisson's ratio and Young modulus of both pSi and silicon<sup>4,5</sup>. The coefficients  $d$  and  $m$  are calculated from knowledge of  $W(r)$ ,  $V(r)$  and  $\gamma$ .

A curvature sensor<sup>3,7</sup> measured the wave front, by comparing the intensity distribution when focused on the sample ( $z = 0$ ), and at a small distance away ( $z = \Delta z$ ). The Transport of Intensity Equation<sup>3,7</sup> relates the intensity  $I$  and the phase  $\varphi$  along the path  $z$  by:

$$\frac{\partial \varphi}{\partial \mathbf{n}} + \delta(e) \frac{\partial \varphi}{\partial \mathbf{n}} \approx \frac{-k}{I_0} \frac{\partial I(\mathbf{r}, z)}{\partial z} \approx -2k \frac{I_0 - I(\mathbf{r}, \Delta z)}{I_0 \Delta z}; \quad \frac{\partial^2}{\partial^2 x} + \frac{\partial^2}{\partial^2 y}; \quad k = \frac{2\pi}{\lambda}, \quad (2)$$

where  $\mathbf{n}$  is the normal vector at the edge  $e$  of the measured sample. The boundary conditions  $\partial \varphi / \partial \mathbf{n}$  are measured through the intensity at the round edge  $e$  ( $\mathbf{r} = \rho$ ).  $I_0 = I(\mathbf{r}, z = 0)$  is the intensity measured (only once) as focused on the sample or just before it. It is constant, and so is the phase; any changes due to strain will be limited to the second plane. Subtracting two

measurements with and without voltage,  $I_V(\mathbf{r})$  and  $I_N(\mathbf{r})$ , the in-focus measurement  $I_0(\mathbf{r})$  will drop out. The wave front  $W(\mathbf{r})$  is deduced from solving<sup>7</sup>

$$I_V(\mathbf{r}) - I_N(\mathbf{r}) \approx z I_0(\mathbf{r}) \gamma^2 W(\mathbf{r}) + \delta(\rho) \partial\phi/\partial\mathbf{n} \quad (3)$$

We measured different wafers at different voltages and assessed the curvature near the electrodes (Fig. 1). At 60% porosity,  $E_{ps} \approx 18.8$  GPa,  $\nu_{ps} \approx 0.09$  while for silicon  $E_{Si} = 107$  GPa,  $\nu_{Si} \approx 0.26$ . The piezoelectric constant was found to be  $d \approx -5$  to  $-100$  nm/V and the electrostrictive (quadratic) constant  $m = 1.2$  to  $6$  nm/V<sup>2</sup> (Eq. 1, Table 1). Isotropy of these constants was assumed even though in *n*-type pSi the pores are essentially normal to the layer. Some of the non-quadratic response apparently arose from the voltage distribution between the electrodes on the non-conductive pSi side. Lack of means prevented us from probing further into the sources of the large variations in  $d$  and  $m$ , due to uncertainty in layer depth and in  $\gamma$ . Slight variations in doping and processing can lead to significant changes in homogeneity, uniformity, oxidation and depth of the porous material<sup>6</sup>. Sample colors, from dark yellow to gray, are another proof for this variability.

The response of the material reached its peak strain only after a minute of applied voltage or illumination, as measured by a time series of images (Figs. 2, 3). We have tried, even prior to other experiments<sup>8</sup>, to apply audio range signals to the samples, but could not elicit any audible or other response.

The piezoelectric and electrostrictive response of the pSi can be attributed to a number of processes, such as electrostatic pull between the porous islands, governed by the absolute value of the charge (or  $V^2$ ). The slow response could be caused by current channels developing in the material. Alternatively Joule heating of the pSi could be a source for the measured strain or part of it<sup>8</sup>. The applied power was either the product of the current  $I$  and the voltage on the sample, or the light intensity on it. The  $I$ - $V$  characteristics were typical and both odd, while the voltage dependence of the strain was nearly even. Heating of the samples could also occur because of creation of plasma in the pSi. In some samples the voltage was limited to 50-200V, possibly due to breakdown and plasma formation in the passivated pSi, the pore size varying between samples.

Illumination of the pSi with a 6 mW HeNe laser had a similar but much weaker effect (Fig. 3). It is possible that this piezooptic response is a secondary result of voltage developing in the illuminated pSi. This raises the option of controlling the shape of the mirror optically rather than electronically.

## REFERENCES

1. E. N. Ribak, 'Deformable mirrors', in *Adaptive Optics in Astronomy*, NATO ASI **423**, 1994.
2. M. A. Ealey, *SPIE* **1543**, 346, 1991.
3. R. K. Tyson, Ed., *Adaptive Optics Engineering Handbook*, Marcel Dekker, 2000.
4. E. Steinhaus and S. G. Lipson, *J. Opt. Soc. Am.* **69**, 478, 1979.
5. C. Schwartz, E. Ribak, and S. G. Lipson, *J. Opt. Soc. Am.* **A 11**, 895, 1994.
6. L. Canham, Ed., *Properties of Porous Silicon*, INSPEC 1997.
7. E. N. Ribak and S. Vinikman, in *Adaptive Optics for Industry and Medicine*, Ed. G. D. Love, World Scientific, 1999.
8. H. Shinoda, T. Nakajima, K. Ueno, and N. Koshida, *Nature* **400**, 6747, 853, 1999.

TABLE 1

Responses in three typical samples, measured near the electrode or illuminated area.

sample	total Si thickness $\mu\text{m}$	pSi thickness $\mu\text{m}$	wafer diameter mm	prefactor $\gamma$	piezoelectric constant $d$ nm/V	electrostrictive constant $m$ nm/V <sup>2</sup>	response full time s	response to light nm/mW
1	200	50	25.4	$15.5 \cdot 10^7$	-5.2	6.0	180	20-30
2	400	50	50.8	$1.45 \cdot 10^7$	-96	2.3	90	10-30
3	400	50	50.8	$1.45 \cdot 10^7$	-49	1.2	180	20-60

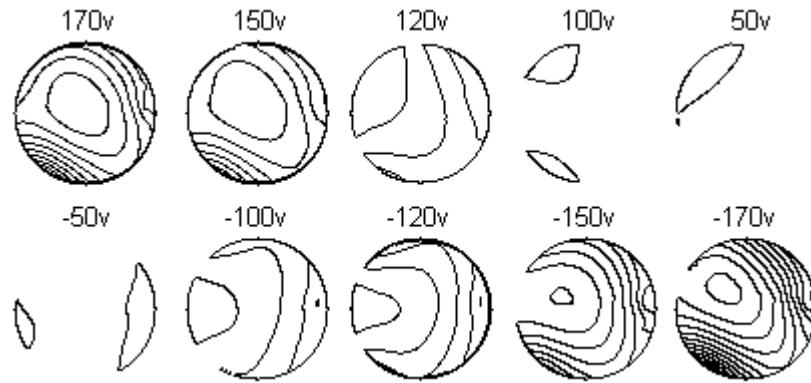


Figure 1. Voltage dependence of the silicon-porous silicon bimorph: variation in the wave front reflected off the mirror in contour steps of  $0.15 \mu\text{m}$ . The visible section shows 15 mm of sample 1, with two electrodes, at the bottom right and at the top left, with a near-central maximum.

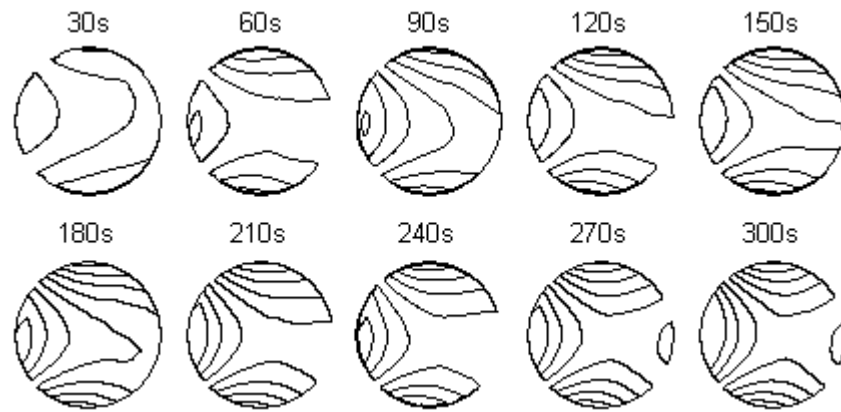


Figure 2: Temporal dependence of the wave front returned from the wafer, under a constant voltage of 120V. A saddle shape develops (contour steps  $0.1 \mu\text{m}$ ). Maxima at top and bottom.

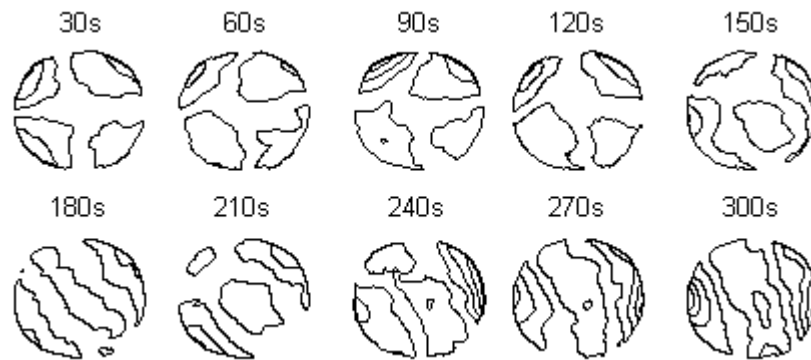


Figure 3: Temporal dependence under a constant illumination of 6 mW. The saddle shape, with maxima at top left and bottom right, develops into a ridge (contour steps  $0.04 \mu\text{m}$ ).