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Materials selection in mechanical design for microsensors and microactuators

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Abstract

Microsensors and microactuators are vital organs of microelectromechanical systems (MEMS), forming the interfaces between controller and environment. They are usually used for devices ranging in size at sub-millimeter or micrometer level, transforming energy between two or more domains. Presently, most of the materials used in MEMS devices belong to the silicon material system, which is the basis of the integrated circuit industry. However, new techniques are being explored and developed, and the opportunities for MEMS materials selection are getting broader. The present paper tries to apply 'performance index' to select the material best suited to a given application, in the early stage of MEMS design. The selection is based on matching performance characteristics to the requirements. A series of performance indices are given to allow a wide range comparison of materials for several typical sensing and actuating structures, and a rapid identification of candidates for a given task.

Keywords: Microelectromechanical systems; Materials selection; Mechanical design; Performance index; Microsensors; Microactuators

1. Introduction

Materials selection is essential for efficient design of microelectromechanical systems (MEMS). For MEMS designers, one of the key jobs for achieving the high level of reliability, low unit cost and optimal function performance of microelectromechanical devices is to carefully choose materials from a limited set. Now, silicon-based materials, which have been commonly used in the semiconductor integrated circuit industry, remain the primary choices for MEMS. These materials form the vast majority of micromachined devices [1]. The restriction to this set of materials ensures compatibility with the process and therefore permits a high degree of integration on a single chip.

Though the silicon-based material set for MEMS is somewhat restrictive, a wide range of other materials is to be exploited. Fabrication processes for glass and quartz are mature and well established. For other materials, such as silicon carbide [2], new techniques are being explored. Also, materials deriving from the carbon material system, such as diamond and amorphous carbon, have recently emerged as promising candidates to improve MEMS mechanical performance [3]. Besides the silicon-based technology, using LIGA technique [4] permits consideration of any material that can be electroplated from solution. These facts enrich the inventory of available MEMS materials.

Furthermore, nanoelectromechanical systems (NEMS) are evolving, with new technical applications emerging. The nanoscale studies often involve a wider range of materials, allowing access to new sensing and actuating methods. For instance, carbon nanotubes exhibit exciting mechanical properties such as high stiffness and axial strength [5]. Thus, the opportunities for NEMS/MEMS materials selection are to be broadly expanded, enabling higher performance mechanical elements. The objective of the present paper is to apply 'performance index' proposed in [6] to evaluate the materials available for microsensors and microactuators.

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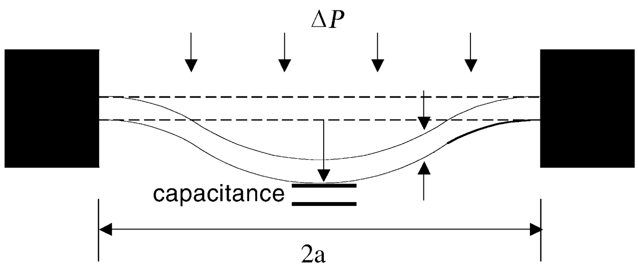

Fig. 1. The deflection of a diaphragm by pressure.

2. Performance index

Performance index is such a criterion in 'Ashby method' [6], providing a comparison between material candidates for a given design. This idea is based on the following systematic analysis.

Three things specify the design of structural elements: the functional requirements, the geometry, and the properties of the material. The performance of an element is described by an equation of the form as [6]:

$$p=f\{(\text{Function}), (\text{Geometry}), (\text{Material})\} \quad (1)$$

or

$$p=f(F, G, M) \quad (2)$$

where p describes some performance aspects of the component: its mass or volume, or cost, or life for example. Optimal design is the selection of the material and geometry, maximizing or minimizing p according to its desirability. The optimization is subject to constraints, some of which are imposed by the material properties, M.

The three groups of parameters in Eq. (2) are said to be 'separable' when the equation can be written as:

$$p=f_1(F)\cdot f_2(G)\cdot f_3(M) \quad (3)$$

When the groups are separable, the optimal subset of the materials can be identified without solving the complete design problem, or even knowing all the details of F and G. This enables enormous simplification. The performance for all F and G is maximized by maximizing $f_3(M)$, which is called 'performance index'.

There are diversiform mechanical elements used as sensing or actuating structures in MEMS [7,8]. It has come out that the objectives and constraints in MEMS design are various. We will consider how to deal with materials selection in practical cases.

3. Performance indices for microsensors

The suitability of a microsensor for a particular application is essentially determined by its characteristic performance. Different applications require different sensor performance. For example, the pressure in a petroleum gas pipeline normally does not need to be measured very precisely, while the devices must endure the high pressure, so pressure sensors for this application are expected to have a large range. In another case, microsensors used to detect poisonous vapor must be very acute; here sensibility is the performance to be improved.

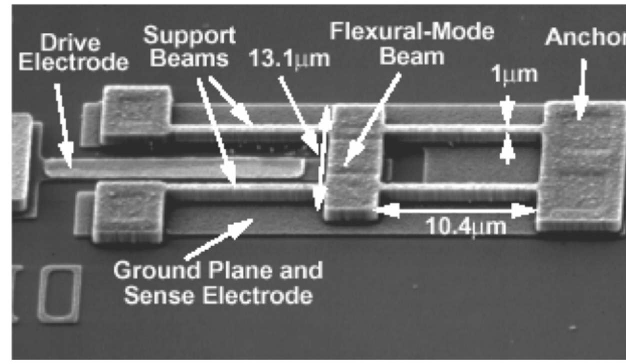

Fig. 2. SEM of a 92 MHz free-free beam polysilicon resonator [9].

3.1. Diaphragms for pressure sensors

Fig. 1 shows a diaphragm of radius a and thickness t, which is used to measure pressure in an indirect route: the diaphragm deflects by pressure, and then the deflection can be converted to an electrical signal via sensing the variance of the capacitance. The deflection δ of the center of the diaphragm caused by ΔP is:

$$\delta=\frac{C_1\Delta P a^4(1-\nu^2)}{Et^3} \quad (4)$$

where C_1 is a constant depending on boundary conditions, E is the Young's modulus, and ν is the Poisson's ratio.

We wish to maximize the deflection δ for measuring higher pressure. It is subject to the constraint that the material remains elastic, that is, the stress in it is everywhere less than the yield or fracture stress, σ_f, of the material. The maximum stress in the diaphragm is:

$$\sigma_f=C_2\Delta P\frac{a^2}{t^2} \quad (5)$$

where C_2 is a constant depending on boundary conditions.

The radius of the diaphragm is determined by the design; the thickness t is free. Eliminating t between Eqs. (4) and (5) gives:

$$\delta=\frac{C_1}{C_2^{3/2}}\left(\frac{a}{\Delta P^{1/2}}\right)\left(\frac{\sigma_f^{3/2}}{E}(1-\nu^2)\right) \quad (6)$$

The best material for the diaphragm is that with the largest value of $M=\sigma_f^{3/2}/E$ [6].

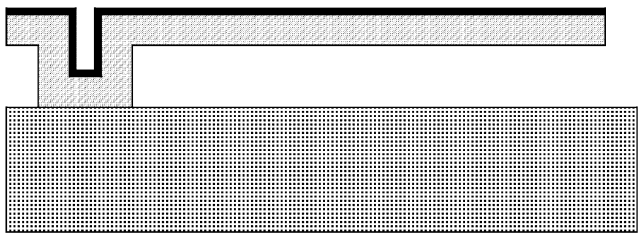

Fig. 3. A microcantilever with specific coating.

3.2. High frequency vibrating elements

Mechanical resonant elements can oscillate at high frequencies and be used as radio frequency devices as Fig. 2 shows. The natural vibration frequency f of a high frequency vibrating element depends strongly upon its material properties as:

$$f \propto \frac{1}{L}\sqrt{\frac{E}{\rho}} \tag{7}$$

where E, ρ and L are the Young's modulus, density and characteristic length of the element, respectively. Therefore, high $\sqrt{E/\rho}$ gives high natural vibration frequency, the best material for this application is the one with the largest value of $M=E/\rho$.

Because of the high inherent modulus and relative low density, carbon nanotubes possess extraordinary performance for resonant applications. According to [10,11], carbon single-walled nanotubes (SWNT) have Young's modulus exceeding 1 TPa, which almost equals the modulus of diamond. Comparing with silicon, the modulus of SWNT is several times higher, while the density is only the half. Therefore, the resonant performance index of SWNT resulting in E/ρ is one order of magnitude higher than current materials for MEMS. This predicts advantage of carbon nanotubes in resonant applications.

3.3. Microcantilever sensors

Fig. 3 shows a microcantilever with specific coating, which is used to detect mercury vapor, moisture, or volatile mercaptans by showing the resonance frequency variation. The resonance frequency, f, of an oscillating cantilever can be expressed as [12]:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{m^*}} \tag{8}$$

where K is the spring constant and m^* is the effective mass of the cantilever. For the case of a rectangular cantilever, $m^*=0.24m_b$, where m_b is the mass of the beam. It is obvious that the resonance frequency will shift due to change in the mass as well as change in the spring constant. This shift in frequency can be written as:

$$df(m^*,K) = \left(\frac{\partial f}{\partial m^*}\right)dm^* + \left(\frac{\partial f}{\partial K}\right)dK = \frac{f}{2}\left(\frac{dK}{K} - \frac{dm^*}{m^*}\right) \tag{9}$$

For a rectangular cantilever, the spring constant, K, is:

$$K = \frac{Ewt^3}{4L^3} \tag{10}$$

where E is the Young's modulus and w, t, L are the width, thickness and length of the beam, respectively. Assuming that the contribution from variation in the spring constant is small, a mass dependence of the fundamental frequency can be written as:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{m^*}} = \frac{t}{2\pi(0.98)L^2}\sqrt{\frac{E}{\rho}} \tag{11}$$

where ρ is the density of the material. Here sensitivity matters. The mass sensitivity of the structure is given by:

$$S_m = \lim_{\Delta m \to 0} \frac{1}{f}\frac{\Delta f}{\Delta m} = \frac{1}{f}\frac{df}{dm} \tag{12}$$

Applying this definition to the case discussed above, the sensitivity of the cantilever-adsorbate system is:

$$S_m = C\left(\frac{1}{wtL}\right)\left(\frac{1}{\rho}\right) \tag{13}$$

where C is a constant. For high mass sensitivity, the best material for a cantilever is that with the largest value of $M=1/\rho$.

4. Performance indices for microactuators

Microactuators provide drive and motion for a variety of requirements. In some applications, the actuating elements are expected to store energy, such as microsprings and flywheels of micromotors. Here, the objective is to maximize stored energy per unit mass or volume. In other cases, quite a number of microactuators are based on shape-changing mechanism, such as thermal expansion, piezoelectric, shape memory alloy and magnetostrictive. These actuators are defined to be work-producing machine and high work output is welcome.

4.1. Rotating disks for micromotors and micropumps

Micromotors and micropumps (shown as Fig. 4) manage liquid or gas at microlevel. The energy stored in a flywheel of radius R, thickness t and density ρ is:

$$U = \frac{1}{2}J\omega^2 \tag{14}$$

where $J=\pi\rho R^4 t/2$ is the inertia moment of the disk, ω is the angular velocity.

The quantity to be maximized is the kinetic energy per unit mass:

$$\frac{U}{m}=\frac{J\omega^2/2}{\pi R^2 t\rho}=\frac{1}{4}R^2\omega^2 \quad (15)$$

The maximum principal stress in a spinning disk of uniform thickness is:

$$\sigma_{\max}=\left(\frac{3+\nu}{8}\right)\rho R^2\omega^2 \quad (16)$$

where ν is the Poisson's ratio. Eliminating $R\omega$ from Eq. (15) and Eq. (16), the kinetic energy per unit mass can be written as:

$$\frac{U}{m}=\left(\frac{2}{3+\nu}\right)\left(\frac{\sigma_f}{\rho}\right) \quad (17)$$

The best material for high performance flywheels is that with the largest value of the performance index, $M=\sigma_f/\rho$ [6].

4.2. Microsprings

MEMS springs come in many shapes and have many purposes. Fig. 5 shows a leaf spring and a helical spring. Regardless of their shapes, the primary function of springs is to store elastic energy and release it again when required.

The elastic energy stored per unit volume in a block of material stressed uniformly is:

$$U=\frac{1}{2}\frac{\sigma^2}{E} \quad (18)$$

where E is the Young's modulus and σ is the uniform stress. It is U that we wish to maximize. A spring will be damaged if the stress σ exceeds its yield or fracture stress, σ_f, so the constraint is $\sigma\le\sigma_f$. The maximum energy density is:

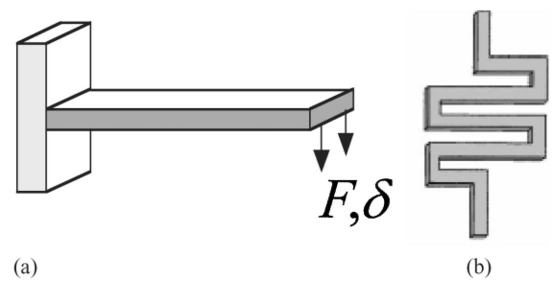

Fig. 5. (a) Leaf spring; (b) helical spring.

$$U=\frac{1}{2}\frac{\sigma_f^2}{E} \quad (19)$$

Leaf springs are less efficient than axial springs because much of the material is not fully loaded. For such cases:

$$U=\frac{1}{2\eta}\frac{\sigma_f^2}{E} \quad (20)$$

where η is a constant more than unity. Thus, the best material for microsprings is that with the largest value of $M_1=\sigma_f^2/E$

If weight, rather than volume, matters, we must divide M_1 by the density ρ, and seek the materials with high value of $M_1=\sigma_f^2/\rho E$.

4.3. Compact single stroke actuators (levers)

Consider the following generic problem: a microactuator is required to be capable of providing a prescribed force F, and a prescribed displacement δ in a single stroke. The volume, V, of the actuator is to be minimized. The actuator has length L, cross-sectional area A and mechanical advantage r, as shown in Fig. 6.

The maximum value of actuation stress in a single stroke, $\sigma_{\max}$, and the maximum actuation strain, $\varepsilon_{\max}$, are basic characteristics of an actuator. Some $(\sigma-\varepsilon)$ curves during a single stroke producing maximum work

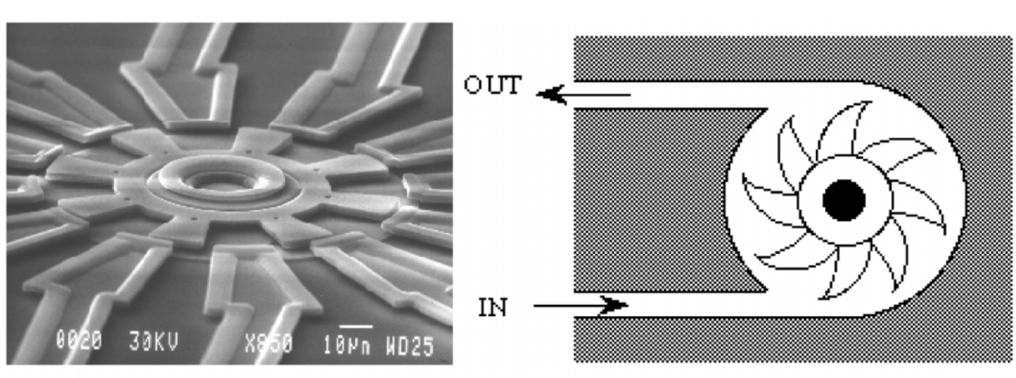

Fig. 4. Rotating disks for (a) micromotor [13]; (b) micropump.

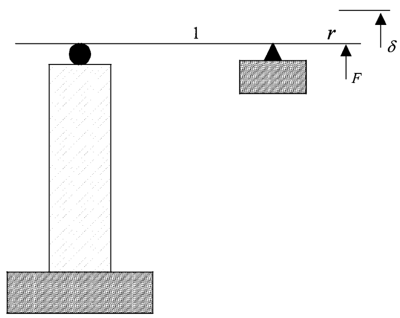

Fig. 6. A lever single stroke actuator.

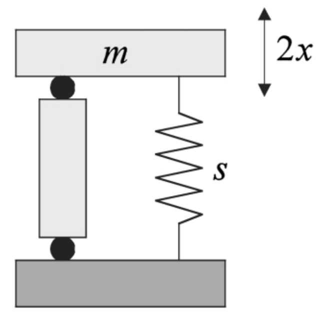

Fig. 8. An actuator used to damp a simple oscillator.

output are shown in Fig. 7. It must be pointed out that the $(\sigma-\varepsilon)$ curves depend on the control signals and external constraints. The shapes shown in Fig. 7 were found by a variety of experimenters [14,15].

The product $\sigma_{max}\varepsilon_{max}$ is an estimate of the maximum work per unit volume in a single stroke. More precisely, a dimensionless stroke work coefficient C_s can be defined as:

$$C_s=\int_0^1 \frac{\sigma}{\sigma_{max}}\mathrm{d}\left(\frac{\varepsilon}{\varepsilon_{max}}\right) \qquad (21)$$

The coefficient C_s lies in the range zero to unity. It is an efficiency measure of the $(\sigma-\varepsilon)$ curves. According to Fig. 7, it can be inferred that present man-made actuators have lower efficiency than natural muscles of animals.

There are constraints both on L and A. The constraint on length arises because the actuator must achieve displacement δ, but has a limited strain ε_{max}, so:

$$\delta\le L\varepsilon_{max}r \qquad (22)$$

Similarly, the prescribed force F must be achieved using limited stress σ_{max}, so:

$$F\le\frac{A\sigma_{max}}{r} \qquad (23)$$

Volume, $V=AL$, is to be minimized. Substituting the two constraints gives [16]:

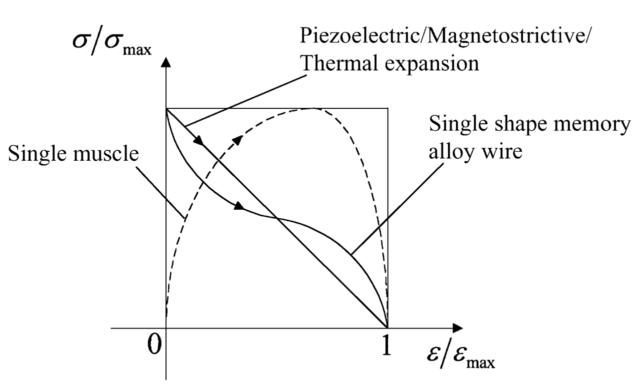

Fig. 7. Normalized single stroke stress vs. strain curves.

$$V\ge\frac{F\delta}{\sigma_{max}\varepsilon_{max}} \qquad (24)$$

To minimize the volume, the product $\sigma_{max}\varepsilon_{max}$ must be maximized, so $\sigma_{max}\varepsilon_{max}$ is the performance index for this problem. If the mass of the actuator is to be minimized, $\sigma_{max}\varepsilon_{max}/\rho$ becomes the performance index. If it is desirable to maximize the stroke work per unit volume, $C_s\sigma_{max}\varepsilon_{max}$ is then the performance index.

4.4. An actuator used to damp a simple oscillator

Consider a simplified system consisting of an undamped mechanical oscillator with stiffness s, vibrating with initial amplitude x_0. An actuator of cross-sectional area A and length L is attached as shown in Fig. 8. The actuator is intended to remove energy from the oscillating system and bring it to rest in a prescribed number of cycles, N, where $N\gg 1$.

The maximum elastic energy stored in the oscillator at amplitude x is $U=sx^2/2$. During each cycle, the amount of energy that the actuator can remove depends on its cyclic stress vs. strain characteristic, its volume and the amplitude of oscillation. An example of the stress vs. strain characteristic with varying strain amplitude is shown in Fig. 9.

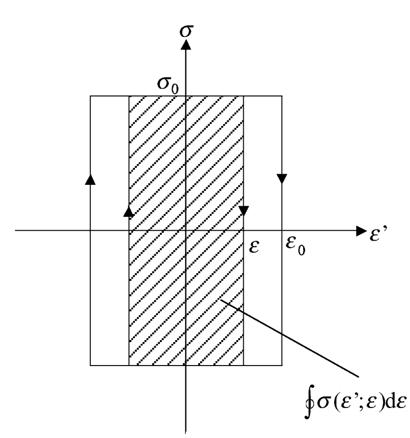

Fig. 9. Cyclic stress vs. strain at varying strain amplitude [16].

Table 1
Material performance indices for several micromechanical elements

Material	Density, ρ (Kg/m^3)	Young's modulus, *E* (GPa)	Fracture strength, σ_f (MPa)		
Silicon	2330	168	4000		
Silicon oxide	2200	73	1000		
Silicon nitride	3300	304	1000		
Nickel	8900	207	500		
Aluminum	2710	69	300		
Aluminum oxide	3970	393	2000		
Silicon carbide	3300	430	2000		
Diamond	3510	1035	1000		
Carbon single-walled nanotubes (SWNT)	1330	>1000	–		
	E/ρ (MN/Kg·m)	σ_f/ρ (MN/Kg·m)	$\sigma_f^{3/2}/E$ ($\sqrt{Mpa}$)	σ_f^2/E (MPa)	$\sigma_f^2/\rho E$ (KN/Kg·m)
Silicon	72	1.7	1.5	95	41
Silicon oxide	36	0.45	0.43	14	6.4
Silicon nitride	92	0.30	0.10	3.3	1.0
Nickel	23	0.06	0.54	1.2	0.13
Aluminum	25	0.11	0.75	1.3	0.48
Aluminum oxide	99	0.50	0.228	10	2.5
Silicon carbide	130	0.303	0.208	9.3	2.8
Diamond	295	0.28	0.31	0.97	0.28
Carbon single-walled nanotubes (SWNT)	>752	–	–	–	–

In the *n*th cycle, the oscillator has amplitude x and the actuator dissipates work of magnitude $AL\oint\sigma(\varepsilon';\varepsilon)d\varepsilon'$, where the strain amplitude of the current cyclic $\varepsilon=x/L$, and $\sigma(\varepsilon';\varepsilon)$ is the stress corresponding to a strain ε' in the cycle with strain amplitude ε. The dissipation per cycle is:

$$\frac{d}{dn}\left(\frac{1}{2}sx^2\right)=-AL\oint\sigma(\varepsilon';\varepsilon)d\varepsilon' \tag{25}$$

which, on substituting for $x=\varepsilon L$ and integrating, may be rearranged to the form:

$$\int_0^N \frac{A}{sL}dn=\frac{AN}{sL}=\int_0^{\varepsilon_0}(\varepsilon/\oint\sigma(\varepsilon';\varepsilon)d\varepsilon')d\varepsilon \tag{26}$$

The right-hand side of Eq. (26) is a characteristic of the actuator and is a function of the initial strain amplitude ε_0. It is convenient to express this in non-dimensional form by introducing a damping coefficient C_d, which is defined as:

$$\frac{1}{C_d(\varepsilon_0,\sigma_0)}=4\frac{\sigma_0}{\varepsilon_0}\int_0^{\varepsilon_0}(\varepsilon/\oint\sigma(\varepsilon';\varepsilon)d\varepsilon')d\varepsilon \tag{27}$$

where σ_0 is the initial stress amplitude. The damping

Table 2
Material performance indices for several shape-changing microactuators

Actuator material	Maximum actuation strain, ε_{max}	Maximum actuation stress, σ_{max} (MPa)	Stroke work coefficient, C_s
Low strain piezoelectric	5×10^{-6}–3×10^{-5}	1–3	≈0.5
High strain piezoelectric	5×10^{-5}–2×10^{-4}	4–9	≈0.5
Piezoelectric polymer	2×10^{-4}–1×10^{-3}	0.5–5	≈0.5
Thermal expansion (10 K)	9×10^{-5}–3×10^{-4}	20–50	≈0.5
Thermal expansion (100 K)	9×10^{-4}–3×10^{-3}	200–500	≈0.5
Magnetostrictor	6×10^{-4}–2×10^{-3}	90–200	≈0.5
Shape memory alloy	7×10^{-3}–7×10^{-2}	100–700	0.3–0.6
	Young's modulus, E (GPa)	Density, ρ (Kg/m^3)	
Low strain piezoelectric	90–300	2600–4700	
High strain piezoelectric	50–80	7500–7800	
Piezoelectric polymer	2–10	1750–1900	
Thermal expansion (10 K)	70–300	3900–7800	
Thermal expansion (100 K)	70–300	3900–7800	
Magnetostrictor	40–200	6500–9100	
Shape memory alloy	30–90	6400–6600	

coefficient is in the range zero to unity. Setting $\sigma_0 = \sigma_{max}$ and ε_0 equals the maximum cyclic strain amplitude, which can be achieved, gives the maximum value of C_d. The volume V of the actuator is:

$$V = AL = \frac{sx_0^2}{4NC_d\sigma_{max}\varepsilon_0} \quad (28)$$

To minimize the volume, $C_d\sigma_{max}\varepsilon_0$ is the performance index for this problem [16].

5. Conclusions

Performance indices for microsensors and microactuators, as listed in Tables 1 and 2, allow a broad comparison of materials for given tasks in the early stage of MEMS design. Such a comparison leads a loss of precision, some aspects of the behavior of individual application are neglected, and it has been assumed that the mechanical principles apply equally to microscale devices as those at normal scale. In practice, scale effects influence the choice of materials. These aspects could be included in more detailed analysis. The benefit of the simplification is to help in selecting the most appropriate material from candidates rapidly. Materials selection based on performance index gives a systematic, convenient, and approximate way to approach design problems. It must be recognized that the structures used in MEMS devices are diversiform, and the performance index for a individual task must be derived from its physical model, i.e. its mechanical structure, requirement, objective and constraint.

Acknowledgments

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