Material Selection for MEMS Devices

Rudra Pratap & A. Arunkumar
CranesSci MEMS Lab, Department of Mechanical Engineering, Indian Institute of Science,
Bangalore, 560 012
Received 7 June 2006; revised 24 November 2006; accepted 1 November 2006

As MEMS design matures and migrates from process centric design to performance based design, MEMS designers would need a rational method for selecting an appropriate material that is not based on ease of processing alone. While there is a growing number of thin film materials that can be used in micromachining for MEMS devices, the selection of a particular material is rarely based on quantifiable criterion that relates directly to the optimum performance of the device. In this study, we present a methodology for creating material related device performance indices that can be used for selecting best possible material for a device. This study is inspired by the Ashby approach and its extension to the microworld in recent studies, where materials are graded on material performance indices and the most appropriate material is selected from the Ashby charts so created. We extend this concept further in this paper and create device performance indices that can be used to grade MEMS materials in performance parameter space. We first create and discuss a material index for thermoelastic damping, an important index for vacuum packed dynamic MEMS devices that has been missing from the list of performance indices previously considered. We present two case studies of material selection, for a MEMS gyroscope and a MEMS ultrasound transducer, to illustrate the methodology and show two different approaches for creating optimality criterion in the presence of several competing performance indices.

Keywords: MEMS devices, Material Performance indices, Thermoelastic damping, MEMS gyroscope, MEMS Ultrasound transducer
IPC Code:

1 Introduction

The most significant contributor perhaps, to the rapid growth of the field of MEMS is the suitability of silicon as a mechanical material\(^1\). Starting from the revolutionary idea of a resonant gate transistor\(^2\) in 1967 to the micromotor fabrication in the late eighties and early nineties\(^3\), and now myriad devices for various applications, MEMS is fast maturing into a formidable technology. The field of MEMS is proving its potential to become a pervasive technology for sensors and actuators, and possibly also for power generation. As various advantageous scaling properties of materials and physical phenomenon are exploited, the diversity and acceptance of MEMS devices keep growing.
While potential of MEMS is well reflected in rapidly growing research in various types of devices, the approach to realization of these devices has mostly been process centric. The effort happens to be much more on realization of a device than obtaining an optimum performance from the device. However, as the fabrication processes mature and get standardized, the approach will change from process centric to design centric as is the case in the macro world.

In product development, it has been observed that a product design undergoes three stages. The first stage is the conceptual design where the stress is on proof of concept, usually in the form of a physically demonstratable idea or principle. The second stage may be called an embodiment design, where the goal is to realize a prototype using first-cut approximate analysis and optimization methods and is accomplished using approximate material properties. The third stage is the final stage of detailed design and analysis where the emphasis is on rigorous analysis, using commercial analysis tools (e.g., FEM) and optimization techniques. At this stage, accurate material properties are used. At present, most MEMS devices are either just completing the first stage of concept design or entering the second stage of embodiment design, where the stress is on overcoming the constraints of processing and widening the scope of productization.

In design, the requirement of optimal performance usually translates into optimization of geometry (shape), topology, and mass of the subcomponent or the structure. Material selection is rarely an exercise in optimization. In fact, material selection is usually dictated by the availability and ease of processing of the material. The popularity of silicon family with MEMS community is largely a result of such selection. However, recent intense research in materials has brought out several materials and processes that show very good promise for competing with silicon. This increase in material space provides an opportunity to designers to evaluate these materials for enhancing the performance of their devices and then select a material for optimal performance. This approach will, thus provide two levels of optimization in device design. To achieve the goal of selecting the best material, a framework is needed that provides a systematic approach of evaluating candidate materials.

Spearing and Romig et al. have addressed a whole range of material issues related to MEMS. While Spearing concentrates on process and design related issues, Romig et al. includes reliability aspect of devices too. Srikar and Spearing have observed that Ashby approach for selection of materials in macro domain can also be used for the same purpose in the micro domain and have extended their study for actuators using material indices proposed by Ashby. Similarly, Jin Quian has compared materials for sensors and actuators using these material indices. Although all these papers have used the Ashby chart, the current study is unique in following a device approach. We show how the indices used in the Ashby chart can be combined to generate device performance indices and then used effectively to plot.
candidate materials for ranking them for a particular device. While carrying out this analysis, we realized that one important material index missing from the list of available indices from previous studies and particularly relevant to MEMS devices is the index for internal energy dissipation or thermoelastic damping. Therefore, we create an appropriate index for this property and include it in this study. Here, we pursue the observation made by Ashby\textsuperscript{10} and well known in the design community that the material design requirement for a device is a problem of multi-objective optimization, where a compromise needs to be made among several, usually conflicting, objectives.

2 MEMS Materials and Ashby Approach

There is an enormous growth in the material set for MEMS today, however, only a few materials can be used in MEMS devices due to difficulties in microfabrication technology. MacDonald et al.\textsuperscript{11} have identified three basic requirements for materials to be used in MEMS: (a) compatibility with semiconductor fabrication technology, (b) good electrical as well as mechanical properties, and (c) intrinsic properties that retard development of high stresses during processing. With the development in processing techniques such as LIGA, stereo lithography and laser micromachining, today, it is possible to realize MEMS devices made-up of four different class of engineering materials – metals like Ni, Al, nonmetals like Si, Ge, GaAs, polymers like SU8, polyimide and ceramics like diamond, SiC, Si$_3$N$_4$, SiO$_2$, etc\textsuperscript{12}. While the use of silicon family in MEMS devices is widely reported, diamond\textsuperscript{13}, may be MEMS material of the future. In this study, we have selected 14 widely used MEMS materials taken from all the relevant groups whose mechanical properties are given in Table I. We have considered properties like Young’s modulus ($E$), density ($\rho$), thermal conductivity ($k$), failure strength ($\sigma_f$), etc, that affect the performance of a MEMS device, Fracture toughness ($K_{IC}$) and coefficient of thermal expansion ($\alpha$), that affect the reliability of the device.
At micro-scale, a banded range of values of material properties has been reported for almost all materials. There are various reasons why a range of values rather than a specific value has been obtained. Some of the prominent reasons are: (a) unavailability of direct measurement techniques owing to specimen size constraints, (b) lack of accurate models that can be used in indirect techniques to interpret data, (c) metrological errors in establishing the geometry of test samples, and (d) variations in physical properties due to high sensitivity to process parameters (e.g., point defect density, dislocations, and grain boundaries are sensitive to deposition process parameters such as temperature, pressure, gas flow rate, etc.). Sharpe provides an extensive survey of the variation in mechanical properties of thin films for MEMS materials. He studies the scatter in property values using the theory of probabilistic Weibull distribution and recommends the most likely value of a property to the designer. Based on this analysis, he recommends typical values to be used for Young’s modulus and yield strength. Spearing extends this analysis to other mechanical properties and relates the recommended values to bulk properties.

In this study, we investigate the Ashby approach. This procedure allows one to make a rational choice of material for any device in the macro world. In the approach, Ashby suggested the performance parameter $P$ of a device is segregated into three domains: functional, geometric and material; and it is assumed that these three domains are independent in affecting the performance of a device. In other words,

$$ P = f(F,G,M) = f(F)f(G)f(M) \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (1) $$

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic Modulus $E$ in GPa</th>
<th>Failure Strength (yield strength and brittle strength for ductile and brittle materials respectively) $\sigma$ in GPa</th>
<th>Thermal Conductivity $K$ in W/m°C</th>
<th>Coef. Of Thermal Expansion $\alpha$ in $\times 10^{-6}$/°C</th>
<th>Cp in J/kg°C</th>
<th>$\rho$ in kg/m$^3$</th>
<th>Fracture Toughness $G$ in MPa m$^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>1000 600 1100</td>
<td>60.5 0 10 6.9 1</td>
<td>5.18 32 3000</td>
<td>5.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiC</td>
<td>400 531 479</td>
<td>7 4 9 3.5 3.3</td>
<td>1540 3600</td>
<td>3.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>250 230 250</td>
<td>6.4 6 8 0.19 0.1</td>
<td>120 3100</td>
<td>1.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO2</td>
<td>70 57 92</td>
<td>1 0.8 1.1 0.0014 0.055</td>
<td>937 2900</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCSi (100)</td>
<td>129.5 115 142</td>
<td>3.4 2 4.3 1.57 2.59</td>
<td>700 420</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCSi (111)</td>
<td>168 147 168</td>
<td>7 6 8</td>
<td>700 420</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poly-Si</td>
<td>159 140 169</td>
<td>1.85 1.21 2.6 0.14 2.8</td>
<td>700 420</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>410 101 144</td>
<td>0.7 2.0 4.5</td>
<td>134.6 1102</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>70 47 66</td>
<td>0.17 0.15 0.3</td>
<td>2.56 26</td>
<td>66.7 2100</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>155 168 214</td>
<td>0.4 0.35 0.76</td>
<td>9.09 9</td>
<td>431.5 1010</td>
<td>95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>120 86 117</td>
<td>0.25 0.12 0.26</td>
<td>3.98 16.5</td>
<td>336.2 3200</td>
<td>65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>110 96 115</td>
<td>0.5 0.44 0.79</td>
<td>0.2 8.5</td>
<td>621 664</td>
<td>45.1 70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si3N4</td>
<td>3 1.8 4.2</td>
<td>0.04 0.03 0.05</td>
<td>0.002 52</td>
<td>114.1 114.1</td>
<td>114.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyimide</td>
<td>8 4 15</td>
<td>0.85 0.0231 0.067</td>
<td>0.0012 20</td>
<td>114.1 1400</td>
<td>31.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVDF</td>
<td>2.3 1.1 4</td>
<td>0.053 0.048</td>
<td>0.08</td>
<td>0.0022 80</td>
<td>114.1 114.1</td>
<td>114.1</td>
<td></td>
</tr>
<tr>
<td>PMMA</td>
<td>2.41 1.6 3.1</td>
<td>0.076 0.048</td>
<td>0.08</td>
<td>0.0022 80</td>
<td>114.1 114.1</td>
<td>114.1</td>
<td></td>
</tr>
</tbody>
</table>
where F, G and M are functional, geometric and material parameters, respectively. This approach converts the problem of optimizing the device performance into optimizing the material performance index, given the functional parameters and the geometry of the device. Thus, the material performance index $f_3(M)$ acts as the basis for comparison and selection of the material for a particular device. The first cut optimization study is carried out initially using performance indices and selection charts. Further narrowing of material set is achieved by using performance charts (plots with their axes corresponding to different performance indices). In the world of MEMS, these charts have some specific characteristics: (a) There is, relatively, a very small material set available for selection. (b) MEMS devices are dominated by plate, beam and their combinational structures. (c) As many of the MEMS devices are used as sensors, reliability of these devices becomes an important parameter to be considered. Ashby\textsuperscript{15} has come out with material performance indices responsible for frequency, deflection, etc, for mechanical elements like plates, beams, etc. Spearing\textsuperscript{7} has extended these indices to MEMS devices. For example, the equations for the fundamental frequency of a beam and that of a plate in flexural mode are given by:

$$\omega_{\text{beam}} = C_1 \left( \frac{h}{L^2} \right) \sqrt{\frac{E}{\rho}}$$  \hspace{1cm} \text{......... (2)}$$

$$\omega_{\text{plate}} = C_2 \left( \frac{h}{a^2} \right) \sqrt{\frac{E}{\rho(1-\nu^2)}}$$  \hspace{1cm} \text{......... (3)}$$

where $C_1$ and $C_2$ are fixity constants, $L$ the length of the beam, $a$ the edge length or radius of the plate and $h$ is the thickness of plate or the beam. The value of Poisson’s ratio for most MEMS materials is $\nu \cong 0.25$. For resonating beams and plates to possess higher flexural vibration frequencies, the performance index $\sqrt{\frac{E}{\rho}}$ has to be maximized. Similarly for beams and plates to have maximum deflection under specified load $\left( \frac{\sigma_f}{E} \right)$ and $\left( \frac{\sigma_{f/2}}{E} \right)$ are the indices to be maximized, respectively. Table 2 gives a list of selected performance indices that are applicable to wide range of devices, along with their applicability criterion and few example devices where these indices can be applied.
Table 2- Performance indices

<table>
<thead>
<tr>
<th>Performance index</th>
<th>Applicability criterion</th>
<th>Applicable device</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{E}{\rho}$</td>
<td>The highest value maximizes natural frequency</td>
<td>Resonators, CMUT, Gyroscopes</td>
</tr>
<tr>
<td>$\left(\frac{\sigma_f}{E}\right)$</td>
<td>A higher value maximizes deflection under specified load for a beam</td>
<td>Accelerometers, switches</td>
</tr>
<tr>
<td>$\left(\frac{\sigma_f^{3/2}}{E}\right)$</td>
<td>A higher value maximize deflection under specified load for a plate</td>
<td>CMUT, Microphones</td>
</tr>
<tr>
<td>$\left(\frac{k}{\alpha}\right)$</td>
<td>A higher value indicates minimum thermal distortion</td>
<td>Microheaters, thermal actuators</td>
</tr>
<tr>
<td>$\left(\frac{\sigma_f}{\rho}\right)$</td>
<td>A higher value indicates maximize inertial force within the limit of failure stress</td>
<td>Micromotors, micropumps and microturbine</td>
</tr>
</tbody>
</table>

Fig. 1 is a sample selection chart for MEMS material that is created with design guidelines of constant $\sigma_f/E$ and $(\sigma_f)^{3/2}/E$ to select materials that would maximize deflection under specified load for beams and plates, respectively. This plot clearly shows the range of these aforementioned performance indices for MEMS materials set. Owing to the variation in thin film properties, the materials have been represented in the form of closed contour (rectangle), rather than single point, in the performance chart, which means that, there is a finite probability for performance index of particular material to lie anywhere within the contour. Still, the relative position of each material, irrespective of point or closed contour in those performance charts remains the same.

With the growing list of resonating MEMS devices, the need to study thermoelastic damping in micro devices has become important. Thermoelastic damping is identified as an important loss mechanism for all types of resonant MEMS devices operating in vacuum environment. Devices with high quality factors are needed for reducing read out errors and power consumption, improving stability, and increasing sensitivity.
Fig. 1- A typical material selection graph based on performance indices. Here, the yield strength $\sigma_f$ is plotted against the Young’s modulus $E$ for MEMS specific thin film materials listed in Table I. The rectangles for each material represent the statistical spread in these properties reported in the literature. The slanted lines represent equal values of performance indices $\sigma_f/E$ and $(\sigma_f)^{3/2}/E$ used for comparing deflection of a beam or plate, respectively, under a given load.

3 Thermoelastic Damping Index

Thermoelastic damping involves coupling of thermal and mechanical domains in a material. This causes loss of energy when the material is subjected to a dynamic environment. A major part of energy, which is supplied to a component, is stored as restorable elastic energy, but a part of it is lost due to various energy dissipation mechanisms. A structure when strained in the regions of compressive and tensile stresses causes a change in the thermal field. With a compressive strain temperature increases, while with tensile strain temperature decreases. Due to this existing thermal gradient within the structure, there is a transfer of energy to attain equilibrium. This results in loss of energy.

The dissipation factor ($Q^{-1}$) for a device vibrating with a frequency $\omega$ is given by:

$$Q^{-1} = \frac{1}{2\pi} \left( \frac{\Delta U}{U} \right) = \Delta \sigma C_\kappa \left( \frac{\omega \tau}{1 + (\omega \tau)^2} \right)$$

\[\text{………… (4)}\]
\( \Delta U \) is the energy lost per cycle, \( U \) the total energy supplied, \( \Delta E \) is a dimensionless quantity called relaxation strength, \( C_g \) the dimensionless geometric constant and \( \tau \) is the relaxation time. The value of \( C_g \) for a thin beam is 1, and for thin plate \( C_g = \frac{1 + \nu}{1 - \nu} \) (the value of Poisson’s ratio for most MEMS material is \( \nu \approx 0.25 \), thus the value of \( C_g \) for a plate is approximately 1.65). The relaxation time \( \tau \) is the measure of time taken to reach thermal equilibrium when there is a thermal gradient. Relaxation time is inversely related to the thermal diffusivity \( \chi \) of the material through the distance of spread of the thermal gradient, i.e., the thickness \( b \) of the device, and is given by \( \tau = \frac{b^2}{\chi} \). Thermal diffusivity \( \chi \) is given by
\[
\frac{k}{\rho C_p}
\]
where \( k \) is the thermal conductivity, \( \rho \) the density and \( C_p \) is the specific heat capacity at constant pressure of the device material.

The dissipation factor \((Q^{-1})\) follows a Lorentzian behaviour as a function of \( \omega \tau \) with maximum value of dissipation \( \Delta E C_g / 2 \) occurring when the period of vibration is of the same order as the relaxation time. When the period of vibration is very small compared to the relaxation time, the system gets hardly any time to relax, resulting in no dissipation. Similarly, when the period of vibration is very large compared to the relaxation time, the system is almost always in equilibrium and therefore, there is almost no transfer of energy.

For a thermoelastic solid, the relaxation strength is given by \( \Delta E = \frac{E \alpha^2 T_o}{C_p} \).

So, the fraction of energy dissipated due to the thermoelastic damping is given by
\[
Q^{-1} = C_g \frac{E \alpha^2 T_o}{C_p} \left( \frac{\omega \tau}{1 + (\omega \tau)^2} \right) \]  \[\text{(5)}\]

The quality factor, \( Q \), is an implicit function of geometry and material properties. However, we can arrive at three distinct regions in which the geometry factors can be eliminated and a material index can be arrived at. These three regions are arrived at on the basis of comparing the time period of vibration \((1/\omega)\) with relaxation time \((\tau)\), which is
approximately of the order of $10^{-5}$ to $10^{-8}$ s. The material performance index for frequency is

$$\sqrt{\frac{E}{\rho}}$$

and relaxation time is $\frac{\rho C_p}{k}$. Comparing the value of $\omega \tau$ to 1, we can arrive at three distinct cases, viz. $\omega \tau << 1$, $\omega \tau \approx 1$, and $\omega \tau >> 1$, and accordingly, the fraction $\frac{\omega \tau}{1+(\omega \tau)^2}$ of Eq. (5) reduces to $\omega \tau$, $\frac{1}{2}$, $\frac{1}{\omega \tau}$ respectively. So the material index $M_i$ for thermoelastic damping of devices operating under these conditions are obtained by separating material parameters in Eq. (5) after incorporating the modifications discussed earlier, and is given by

$$M_1 = \left(\frac{\rho E^3}{k}\right)^{\frac{1}{2}} \frac{\alpha^2}{k} \text{ when } \omega \tau << 1 \quad \text{ .......... (6)}$$

$$M_2 = \frac{E \alpha^2}{C_p} \text{ when } \omega \tau \approx 1 \quad \text{ .......... (7)}$$

$$M_3 = \sqrt{\frac{E}{\rho}} \left(\frac{\alpha^2 k}{C_p}\right) \text{ when } \omega \tau >> 1 \quad \text{ .......... (8)}$$

Generally, the thermoelastic damping index for MEMS devices like gyroscopes and accelerometers operating in the kHz range of frequency is $M_1$, $M_2$ is the thermoelastic damping index for devices like CMUT (Capacitive Micromachined Ultrasonic Transducer), operating in the far kHz or MHz range, $M_3$ is the thermoelastic damping index for devices operating in far MHz or GHz range. A higher value of these indices indicates a higher value of thermoelastic damping ratios in those materials. Table 3 presents the normalized values of thermoelastic damping indices for MEMS materials in all the three cases.
4 Case Studies

Two devices: a vibratory gyroscope and a capacitive micromachined ultrasonic transducer (CMUT) have been studied. Here, we implement the multi objective optimization approach in material selection as suggested by Ashby. While we employ the composite function approach for performance optimization of the vibratory gyroscope, we use the value function approach for the CMUT.

4.1 Vibratory gyroscope
A vibratory angular rate sensor (gyroscope) uses Coriolis force to sense angular rates. As shown in Fig. 2, the sensor typically has one or two proof masses that are driven into vibration in a plane and experience an out-of-plane vibration when subjected to a rotational rate non-parallel to vibration plane. We would like to maximize the response due to Coriolis force, which is given as

$$\Omega = \frac{2mA_d\omega_d \Omega}{\omega_y^2},$$

where $m$ is the proof mass, $A_d$ and $\omega_d$ is the amplitude and frequency of vibration in driving mode, respectively. $\Omega$ is the rate of rotation of the object. Here it seems that density and driving frequency can play an important role and hence high-density material like tungsten may suit our purpose best.

The purpose of gyroscope design is to maximize the response of the proof masses due to Coriolis force i.e. maximize deflection in out of plane, which is given in Ref. 20.

$$A = \frac{2A_d\Omega Q_y}{\omega_y},$$

where $A$, $\omega_y$, and $Q_y$ are amplitude, frequency and quality factor of vibration in the transverse plane respectively. We can develop a composite performance index $M_1$ for deflection by multiplying the material performance indices for quality factor, $k\left(\frac{1}{\rho E^3}\right)^{1/2}\alpha^2$, and frequency, $\sqrt{\frac{E}{\rho}}$, to obtain

$$M_1 = \frac{k}{(E\alpha)^2}.$$

A higher value of $M_1$ essentially means a higher deflection for a given rotational rate, i.e., higher sensitivity.

As we have cantilever beams with mass at the end as the yielding member, we can take second performance index as the deflection capability to maximize the sensitivity.

$$M_2 = \frac{\sigma_f}{E}.$$
A higher value of $M_2$ means a higher value of the maximum achievable deflection, and has a direct impact over the upper cutoff frequency ($\omega_{\text{max}}$) or the upper limit of the bandwidth.

Figure 3 is the performance chart for the gyroscope with its axes corresponding to sensitivity and the composite index. As both these indices have to be maximized, we can limit our choice to the materials within the marked region in the upper right hand side of the chart. Now, if we compare diamond and poly Si, it is clear that both have almost the same value of $M_2 (=\sigma_f/E)$, which means that the upper limit of the bandwidth (upper cutoff frequency) is going to be same for a gyroscope made from either of these materials (of course, with the same geometry) but the sensitivity ($M_1$) of diamond will be at least twice that of polySi making it a more preferred material for inertial grade gyroscopes compared to the widely used polySi. (Note that we have not included single crystal silicon in our discussions as the comparison between single crystal silicon and other material is not straightforward.) On the other hand, Si3N4 beats both polySi and diamond in terms stretching the upper limits of the bandwidth (more than twice the value of $M_2$ for polySi or diamond) while providing the mean value of sensitivity between the two materials.
Fig. 3 - Performance index based material selection chart for a vibratory MEMS gyroscope. The materials enclosed in the upper right hand region have the best values for the chosen performance indices.

### 4.2 Capacitive Micromachined Ultrasonic Transducer (CMUT)

CMUTs (Ref. 19), as shown in Fig. 4, consist of a fixed electrode on the substrate and a membrane electrode that can vibrate. The two electrodes together form a parallel plate capacitor that can generate as well as sense ultrasound signals. The vibrating membrane generates ultrasound waves in its surrounding media, and the same membrane responds by generating an electrical signal when struck by an ultrasound acoustic pressure wave, thus acting as a sensor. CMUTs have a wide range of application in Non Destructive Transducer, biomedical imaging and industrial process control. They prove advantageous over traditional piezoelectric ultrasonic transducers in terms of sensitivity, bandwidth, insertion loss, low impedance mismatch with air and water, size reduction and low cost. The required electronics for signal processing is simple and can be integrated on the same chip. The main structural element of the CMUT, the vibrating membrane or the plate, has been realized using a wide range of materials like polysilicon, SCSi, silicon nitride and PVDF. Here, we set out
to grade all relevant thin film materials from CMUT performance point of view so that we can make optimal material selection for this device.

Fig. 4 - Schematic cross-section of a single CMUT cell

In NDT applications, one is usually concerned about detecting cracks or other such discontinuities inside a material. An empirical rule in industrial inspections is that discontinuities need to be longer than one-half of the wavelength to be detected. Hence to achieve higher sensitivity and resolution (detection of small discontinuities), high frequency ultrasound pulse is required. In principle, CMUTs can generate ultrasound waves of very high frequency. The frequency of the generated wave is determined by the fundamental frequency of the CMUT membrane because it vibrates at resonance. According to Eq. (3), the material index responsible for maximizing flexural vibration frequencies of a plate is

$$M_1 = \frac{E}{\sqrt{\rho}}$$

To generate ultrasound waves having higher intensities, we need to maximize displacement of the CMUT membrane. Similarly, for the CMUT to be sensitive to very low intensity reflected pulse, it is necessary to achieve a sufficient deflection under low force or pressure. The deflection $\delta$ at the center of a circular plate is related to the acoustic pressure $P$ and yield stress $\sigma_f$ through the following Eq. (16)

$$\delta = C_3 \left( \frac{a}{\sqrt{P}} \right) \left( \frac{\sigma_f^{\frac{2}{3}}}{E} \left( 1 - \nu^2 \right) \right) \quad \ldots \ldots \quad (16)$$

The material index to maximize sensitivity (larger deflection under a specified pressure) is, therefore,
In addition, we need to consider the thermal stability of CMUTs as they are frequently required to operate over a wide range of temperatures in NDT applications. Since the dimensional change caused by the change in temperature of operation shifts the fundamental frequency, it affects sensitivity and the bandwidth. Therefore, the thermal stability of performance is an important criterion. The material index that has to be maximized to have sufficiently good thermal stability\(^9,^{15}\) is given by:

\[
M_3 = \frac{k}{\alpha}.
\]

The thermoelastic damping as a performance index has not been considered because such damping is not the major energy dissipation mechanism in CMUTs; the contribution of thermoelastic damping is a few orders of magnitude smaller than that of airflow and squeeze film damping.

Now, with three performance indices of different weightage with respect to the performance of a CMUT, it is necessary to normalize these performance indices and develop a normalized composite index \(P_{\text{norm}}\) that gives the combined effect of all these three. Here, we use the value function approach to arrive at a composite index. If we define \(P_{\text{norm}} = \alpha_1M_1 + \alpha_2M_2 + \alpha_3M_3\) where \(\alpha_i (i = 1, 2, 3)\) are the weights for indices to be decided by the designer so that \(\sum \alpha_i = 1\). The values of performance indices are normalized as:

\[
M_i = \frac{M_i}{(M_i)_{\text{max}}}
\]

On substituting the values of \(M_i\) and \(\alpha_i\) we can arrive at \(P_{\text{norm}}\). The material that has the maximum value of \(P_{\text{norm}}\) is the best candidate for the CMUT. With respect to functionality of the CMUT, the indices for frequency and sensitivity have a higher weightage compared to the index for thermal stability. Therefore, let us take two cases as examples where the weight functions are \(\alpha_1=0.4, \alpha_2=0.4, \alpha_3=0.2\) and \(\alpha_1=0.4, \alpha_2=0.3, \alpha_3=0.3\). We obtain \(P_{\text{norm}}\) for each material in both these cases. Table 4 presents the normalized value of performance indices.
along with the composite index thus obtained. In each case, diamond outperforms other materials followed by silicon nitride (Si$_3$N$_4$) and silicon carbide (SiC).

Table 4 - Normalized material indices and performance indices for a CMUT

<table>
<thead>
<tr>
<th>Material</th>
<th>$M_{21} = \frac{E}{\sqrt{\rho}}$</th>
<th>$M_{22} = \frac{\sigma_f^{3/2}}{E}$</th>
<th>$M_{23} = \frac{K}{\alpha}$</th>
<th>$M_{24} = \frac{\sigma_f^{3/2}}{E \rho}$</th>
<th>$P_{\text{NORM}} = \sum \alpha_i M_{2i}$</th>
<th>$P'<em>{\text{NORM}} = \sum \alpha_i M</em>{2i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>1.00E+00</td>
<td>2.81E-01</td>
<td>1.00E+00</td>
<td>4.97E-01</td>
<td>7.12E-01</td>
<td>7.84E-01</td>
</tr>
<tr>
<td>3H-SiC</td>
<td>7.40E-01</td>
<td>4.20E-01</td>
<td>1.54E-01</td>
<td>5.49E-01</td>
<td>4.95E-01</td>
<td>4.68E-01</td>
</tr>
<tr>
<td>Si3N4</td>
<td>5.94E-01</td>
<td>5.87E-01</td>
<td>3.44E-02</td>
<td>6.17E-01</td>
<td>4.79E-01</td>
<td>4.24E-01</td>
</tr>
<tr>
<td>SiO2</td>
<td>3.50E-01</td>
<td>1.30E-01</td>
<td>3.69E-04</td>
<td>8.02E-02</td>
<td>1.92E-01</td>
<td>1.79E-01</td>
</tr>
<tr>
<td>SCSi (110)</td>
<td>4.96E-01</td>
<td>4.39E-01</td>
<td>9.77E-02</td>
<td>3.86E-01</td>
<td>3.94E-01</td>
<td>3.60E-01</td>
</tr>
<tr>
<td>SCSi (110)</td>
<td>5.65E-01</td>
<td>1.00E+00</td>
<td>9.77E-02</td>
<td>1.00E+00</td>
<td>6.46E-01</td>
<td>5.55E-01</td>
</tr>
<tr>
<td>PolySi</td>
<td>5.50E-01</td>
<td>1.21E-01</td>
<td>1.76E-02</td>
<td>1.18E-01</td>
<td>2.72E-01</td>
<td>2.62E-01</td>
</tr>
<tr>
<td>Tungsten</td>
<td>3.05E-01</td>
<td>1.30E-02</td>
<td>5.73E-02</td>
<td>6.99E-03</td>
<td>1.39E-01</td>
<td>1.43E-01</td>
</tr>
<tr>
<td>Aluminium</td>
<td>3.37E-01</td>
<td>9.08E-03</td>
<td>1.37E-02</td>
<td>5.41E-03</td>
<td>1.41E-01</td>
<td>1.42E-01</td>
</tr>
<tr>
<td>Nickel</td>
<td>3.01E-01</td>
<td>1.24E-02</td>
<td>1.00E-02</td>
<td>6.61E-03</td>
<td>1.28E-01</td>
<td>1.27E-01</td>
</tr>
<tr>
<td>Copper</td>
<td>2.42E-01</td>
<td>9.45E-03</td>
<td>3.47E-02</td>
<td>4.05E-03</td>
<td>1.08E-01</td>
<td>1.10E-01</td>
</tr>
<tr>
<td>Titanium</td>
<td>3.27E-01</td>
<td>2.92E-02</td>
<td>3.41E-03</td>
<td>1.68E-02</td>
<td>1.43E-01</td>
<td>1.40E-01</td>
</tr>
<tr>
<td>SU8</td>
<td>1.06E-01</td>
<td>2.42E-02</td>
<td>5.57E-06</td>
<td>4.54E-03</td>
<td>5.22E-02</td>
<td>4.97E-02</td>
</tr>
<tr>
<td>Polyimide</td>
<td>1.57E-01</td>
<td>1.08E-02</td>
<td>8.70E-06</td>
<td>3.01E-03</td>
<td>6.71E-02</td>
<td>6.60E-02</td>
</tr>
<tr>
<td>PVDF</td>
<td>7.52E-02</td>
<td>4.81E-02</td>
<td>2.75E-06</td>
<td>6.40E-03</td>
<td>4.93E-02</td>
<td>4.45E-02</td>
</tr>
<tr>
<td>PMMA</td>
<td>9.37E-02</td>
<td>7.89E-02</td>
<td>3.99E-06</td>
<td>1.31E-02</td>
<td>6.90E-02</td>
<td>6.12E-02</td>
</tr>
</tbody>
</table>

Alternatively, we can reduce the number of indices to two by merging the frequency index $M_1$ and sensitivity index $M_2$ into a single composite index as both the indices have to be maximized for optimal performance of the CMUT. So, let

$$M_4 = M_1 \times M_2 = \frac{\sigma_f^{3/2}}{E \rho}$$

Thus, we arrive at a two-parameter material space for CMUT performance indices ($M_3$ and $M_4$), which makes selection of materials much easier. Condensing the frequency index $M_1$ and sensitivity index $M_2$ in a single index is sensible because both are implicitly related indices and their evaluation only depends on the material properties of the transducer structure, not its coupling with the surrounding. Also, a multiplicative condensation of the two indices
brings out the strength of each index as opposed to masking the effect of the weaker index if we used an additive condensation (i.e., $M_3+M_4$). Figure 5 is the performance chart for the CMUT with their axis corresponding to $K/\alpha$ and $\sigma_f^{\frac{3}{2}}/(E_p)^{\frac{1}{2}}$. As both these indices have to be maximized, our choice of materials shrinks to those within the marked envelope. Now, if we compare diamond, silicon carbide and silicon nitride on the two indices, we note that all of them have the similar sensitivity (owing to the same value of $M_4$), but the thermal stability of diamond is far superior to silicon nitride and carbide, making it suitable for very high temperature applications such as structural health monitoring of nuclear reactor walls. Also, if we compare polysilicon with silicon nitride, we see that they have almost the same thermal stability but nitride provides four to five times higher sensitivity than polysilicon.

Fig. 5 - Material selection chart for a CMUT. The materials enclosed in the top right hand side rectangular region are the most suitable candidates based on the two chosen performance indices
5. Conclusions

Material selection for MEMS devices following the Ashby approach of material indices has been discussed in this paper. We find that Ashby approach can be of considerable help in evaluating the material space for MEMS devices. To the list of the known material indices useful in evaluating performance of MEMS devices, we add an index for thermoelastic damping that is necessary for evaluating sensitivity of vacuum packed resonant devices. While each index is related to a specific performance parameter, a device usually requires several performance parameters, some of them with conflicting design requirements, to be optimized for enhanced performance of the device. Therefore, a multi-objective optimization approach can be used to evaluate multiple performance indices for the device. We present two examples, one of a MEMS gyro and the other of a CMUT, to illustrate the method of material selection by considering composite performance indices for these devices. We show that despite the overwhelming use of silicon family for such devices, diamond turns out to be a much better material on performance indices. It provides a clear case for developing fabrication processes for materials like diamond.

Acknowledgment

This work is funded by Cranes Software International Limited. The authors thank the National Programme on Smart Materials (NPSM) for providing analysis facilities, and Mr Aravind Pathak for initial discussions on this topic.
References