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A Review on Effects of Mechanical Properties of Thin Film Material, Deposition Process and Characterization Technique For MEMS Applications

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Abstract

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 MEMS 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. Nano mechanical behaviour of thin-film and surfaces has been largely studied during past years in the field of electronics industry such as MEMS, optoelectronics application, aerospace industry, iron and steel industries and also adapted in the field of biological sector that likely to grow in near future extensively. High resolution microscope and computational techniques enable the MEMS material to investigate their interfacial problems at nanoscale. In this paper, we studied the effect of mechanical properties of thin film materials, deposition process and characterization technique for MEMS.

Keywords : MEMS devices, MEMS performance indices, thin film deposition process, material properties

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 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 demonstrated 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, much more on realization of a device than obtaining an optimum performance from the device. However, as the fabrication processes mature and get 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[4] and Romig *et al.*[5] have addressed a whole range of material issues related to MEMS. While Spearing[4] concentrates on process and design related issues, Romig *et al.*[5] include, reliability aspect of devices too. Srikar[6] and

Spearing[7] 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[8,9].Similarly, Jin Quian[10] 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. Therefore, an appropriate index for this property was created and included it in this study. Here, we pursue the observation made by Ashby[11] 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.

The advantage of the present field includes in MEMS application such as diamond like carbon coatings [12], physical vapour deposition coating [13,14] ionic liquids [15], surfactant in interface [16], ceramic coating [17], nano composite coatings [18,19], bio-films [20] and lubricant additive [21]. In order to study MEMS surface at atomic scale new tools are available such as Auger electron spectroscopy (AES), x-ray photon electron spectroscopy (XPS), scanning ion spectroscopy and ion scattering spectroscopy, scanning electron microscope (SEM) and micro-probe analysis [22,23]

Hardness of the coating and stresses developed in the MEMS surface affects the mechanical properties of the thin films. Mechanical property of a coating depends on the type and magnitude of stresses. Coating hardness dominates the wear property of the material. Young's modulus becomes an important calculation part of stress. Less young's modulus may result in low strength demand on MEMS substrate [24]. Internal stresses present in thin-film directly affect adhesion, and generation of crystalline defects. Adhesion of the coating evaluating by the scratch tester[13,14] in which a indenter was moved across the coated surface with increasing load and coating delamination was found. Mechanical properties of coating MEMS surfaces are evaluated by tensile testing, bulge testing, indentation testing, and deflection of micro beams [25]. This has enabled the study of a mechanical behaviour of thin-film and surface coating with accuracy for MEMS application.

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 micro- fabrication technology. MacDonald *et al.*[26] 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 micro- machining, 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, polyimmide and ceramics like diamond, SiC, Si_3N_4, SiO_2, etc[27]. While the use of silicon family in MEMS devices is widely reported, diamond[28], 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.1.We have considered properties like Young's modulus (E), density (ρ), thermal conductivity (K), failure strength (σ_f), etc., that affect the performance of a MEMS device, Fracture toughness (K_{IC}) and coefficient of thermal expansion (α), 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[29] 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 Weibul 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[6] extends this analysis to other mechanical properties and relates the recommended values to bulk properties.

In this study, we investigate the Ashby[8]approach. This procedure allows one to make a rational choice of material for any device in the macro world. In the approach, Ashby[8] 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,

Table 1: Mechanical properties of thin film materials for MEMS[8]

Property Material	Elastic modulus E in Gpa			Failure Strength σ_f in GPa			Thermal Conductivity k W/cm/°C	Coeff of thermal expn α in $10^{-6}/^{o}C$	Specific heat Cp J/kg/k	Density ρ Kg/m^3	Fracture toughness K_{IC} $Mpa(m)^{1/2}$
	Mean value	Lower variation	Upper variation	Mean value	Lower variation	Upper Variation					
Diamond	800	600	1100	8.50	8	10	6.9	1	518	3500	5.9
3H-SiC	400	331	470	7	4	9	3.5	3.3	1340	3200	3.8
Si_3N_4	250	230	290	6.40	5	8	0.19	0.8	170	3100	1.8
$Si0_2$	70	57	92	1	0.8	1.1	0.001	0.55	937	2500	0.8
SCSi(100)	130	115	142	3.4	2	4.3	1.57	2.33	706	2300	1.0
SCSi(110)	168	147	188	7	6	8					
Poly-Si	159	140	169	1.65	1.21	2.8	0.34	2.8	706	2300	1.2
Tungsten	410	NA	NA	0.70	NA	NA	1.78	4.5	135	19300	44
Aluminium	70	47	85	0.17	0.15	0.3	2.36	25	899	2700	20

Nickel	185	168	214	0.40	0.32	0.78	0.899	13	444	8910	95
Copper	120	86	137	0.25	0.12	0.26	3.98	16.6	386	8960	85
Titanium	110	96	115	0.50	0.44	0.79	0.2	8.5	522	4510	70
SU8	3	1.8	4.2	0.04	0.03	0.05	0.002	52	NA	1164	NA
Polyimmide	8	4	15	0.04	0.023	0.07	0.001	20	1100	1420	3.9
PVDF	2.3	1.1	4	0.05	0.048	0.06	0.002	140	1500	1780	3.2
PMMA	2.4	1.8	3.1	0.08	0.048	0.08	0.002	80	1466	1200	NA

$$P = f\,(F,G,M) = f_1(F)\, f_2(G)\, f_3(M) \quad \ldots \qquad (1)$$

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 the 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 devices are dominated by plate, beam and their combinational structures. (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[8] has come out with material performance indices responsible for frequency, deflection, etc, for mechanical elements like plates, beams, etc. Spearing[6] has extended these indices to MEMS devices. For example, the equations for the fundamental frequency (ω) of a beam and that of a plate in flexural mode are given by:

$$\omega_{\text{beam}} = C_1\left(\frac{h}{L^2}\right)\sqrt{\frac{E}{\rho}} \;\ldots. \qquad (2)$$

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

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 material is $\nu = 0.25$. 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 (σ_f / E) and ($\sigma_f^{3/2}$ / E) 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[6,8]

Performance index	Applicability criterion	Applicable device
$\sqrt{\frac{E}{\rho}}$	The highest value maximizes natural frequency	Resonators, Gyroscopes
(σ_f / E)	A higher value maximizes deflection under specified load for a beam	Accelerometers, Switches
$(\sigma_f^{3/2} / E)$	A higher value maximizes deflection under specified load for a plate	Microphones
(k / α)	A higher value indicates minimum thermal distortion	Microheaters, Thermal Actuators
(σ_f / ρ)	A higher value indicates maximize inertial force within the limit of failure stress	Micromotors, Micropumps and Microturbine

Fig. 1 is a sample selection chart for MEMS material that is created with design guidelines of constant (σ_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[6,8]. Still, the relative position of each material, irrespective of point or closed contour in those performance charts remains the same

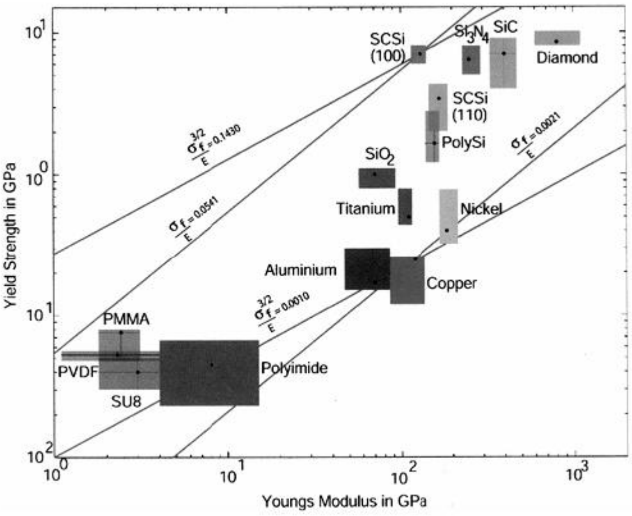


Figure 1: A typical material selection graph based on performance indices [6,8]

Thin Film and Its Characterization

(a)Thin Film deposition process

Physical Vapour Deposition (PVD), Chemical Vapour Deposition (CVD), Thermal Spray (TS) processes are widely used in MEMS industries for coating application [30]. PVD coatings were developed by Faraday in 1852 [31]. It includes three techniques: sputtering, ion plating, and evaporation. PVD process used to apply coatings by condensation of vapour in the vacuum. Perfect adhesion takes place between the atoms of coating material and the atoms of the MEMS substrate. PVD technology is extremely versatile and it ranges from metals, ceramic to paper. In order to improve wear resistance, TiN coating deposited onto high-speed cutting tools nowadays CrN gaining importance due to its corrosion and wear resistance property [32-34]. PVD coated blades in gas turbine industry achieve higher life cycle.

CVD coating introduced in early sixties, it has grown very rapidly in the last thirty year. CVD process involved in fabrication of electronics devices such as semiconductor, optics and also it is used in MEMS applications. CVD process involves deposition of a solid material on a heated surface in vapour phase due to chemical reaction. Thermodynamics plays a vital role in CVD, Kinetics gives transport phenomena and driving force gives direction to the reaction [35].

Inclusion of Gas plasma enhances the process, gives wide control over the residual stresses within the coating and provides thick coating at a higher deposition rate [30]. Thermal spraying coating involves heated material onto the material surface. Wire Flame and Twin-Wire Arc are the most common and cost-effective thermal spray technique producing lower bond strength and with high porosity. Metal, ceramics, alloy, plastic and composites are the common coating materials. Nowadays, use of high velocity oxy flame (HVOF) and twin wire arc (HVOF-Arc) increases continuously. It consists of compressed air and propane. HVOF coatings give less porosity that enables it to resist wear, oxidation, and corrosion. Plasma spray provides good thermal barrier for coating[30, 36 - 40].

(b)Characterization of thin films

Thin film deposition technology has advanced during the last thirty years, and driven due to need for new product and devices in MEMS industry. It is a well establish technology and versatile means of improving component performance. The coating substrate possesses enough toughness to resist stresses and avoid equipment failure. Thin film coating adds physical properties such as hardness, lubricity, and resistance to corrosion, to the lower valued substrate to increase the overall quality of the component [24]. Wide variety of coating is available for the MEMS application. Diamond, diamond like carbon, nitride, and related materials offers new coating strategy which gives significant impact on modern-day life. These days multilayer coating getting attention in tribological application, it reduces friction and wear to considerable limit. This is a hard thick coating consisting of two materials in order to get considerable hardness and to combine the properties of constituent materials [41, 42 - 50].

Optical instruments used to evaluate surface characteristic but nowadays due to technology enhancement surface intrinsic property plays a vital role to explore this area. Thermal characterisation of coating includes differential scanning calorimetry (DSC), differential thermal analysis (DTA), thermomechanical analysis (TMA), thermogravimetric analysis (TGA) and dynamic mechanical analysis (DMA). DSC operates at -1800°C to +7250°C and evaluates heat flow and temperature with chemical reaction with respect to reference MEMS material. Operating condition for DTA is -1800°C to +16000°C and it replaced by DSC due to accuracy. TMA measures dimension changes within the material as a function of time, temperature and operates at -1600°C to +12000°C. TGA measures change in mass as a function of time, temperature. It neither reveals about absorption nor transmission. TGA operates at ambient to 12000°C. DMA gives property of materials under stresses, it detects sample at -1500°C to +5000°C.

A new demand has been arisen in the field of film characterization. Coating technology is interdisciplinary in nature and varies from material to material. Material internal behaviour is an important parameter for surface engineering. To evaluate these internal and outer properties of material and thin-film analytical instruments used to characterise the surface phenomena were listed in Table-3[51,52]. Analytical instruments to analyse surface coating are XRD, SEM, TEM, AES, XPS, SIMS, and RBS. AES has been used to measure the elemental composition to the depth. AES provides the X-ray microanalysis (EDX) information. SIMS measure charge particles scattered from a surface, this gives the thin surface film composition. XRD provides residual stress, grain size, phase composition and texture [53 - 57].

Table 3: Analytical techniques used in thin- film characterization[51,52]

Measurement Technique	Energy Range	Primary Beam and Secondary Signal	Application
SEM	0.3 - 30KeV	Electron - Electron	Surface Morphology
TEM	100 - 400KeV	Electron – Electron	High Resolution Structure
AES	500eV - 10KeV	Electron – Electron	Surface Layer Composition
LEED	20 - 200eV	Electron – Electron	Surface Structure
EMP (EDX)	1 - 30KeV	Electron – X-Ray	Surface Region Composition
STEM	100 - 400KeV	Electron – Electron	X-Ray analysis, Imaging
EELS	100 - 400KeV	Electron – Electron	Local Small Area Composition
SNMS	1 - 15eV	Ion - Atom	Trace Composition Vs Depth
ISS	0.5 – 2KeV	Ion - Ion	Surface Composition
PIXE	1KeV	Ion - X-Ray	Trace Composition
SIM	5 – 20KeV	Photon - Electron	Surface Characterization
XPS	> 1KeV	Photon - Electron	Surface Composition
XRD	> 1KeV	Photon – X-Ray	Crystal Structure
RBS	> 1MeV	Photon - Ion	Composition Vs Depth
XRF	> 1KeV	Photon - X-Ray	Composition (1μm)

***Abbreviation:**
SEM- Scanning Electron Microscopy, TEM- Transmission Electron Microscopy, AES- Auger Electron Spectroscopy, LEED- Low-Energy Electron Diffraction, EMP- Electron Microprobe, STEM- Scanning TEM, EELS- Electron Energy Loss Spectroscopy, SNMS- Secondary Neutral Mass Spectroscopy, ISS- Ion-Scattering Spectroscopy, PIXE- Particle-Induced X-Ray Emission, SIMS- Secondary Ion-Mass Spectroscopy, SIM- Scanning Ion Microscopy, XPS- X-Ray Photo Electron Spectroscopy, XRD- X-Ray Diffraction, RBS- Rutherford Backscattering, XRF- X-Ray Fluorescence [52].

Mechanical Property

Mechanism that affects the nanomechanical behaviour of multilayered systems is image force effect, Orowan strengthening, Hall-Petch behaviour, composition modulation, and coherency and thermal stress [58]. Evaluation of Nanomechanical properties of thin films can split into two methods, first point probes and second complimentary methods. Complementary methods can be used separately or with point probes and it includes Raman spectroscopy to high energy diffraction study [58]. Indentation [25] technique is now most popular due to its simplicity, easiness and widely used to estimate mechanical properties of small volume i.e. thin films.

These days depth sensing device i.e. nanoindentation, used to study the mechanical property of thin films, see Fig.2

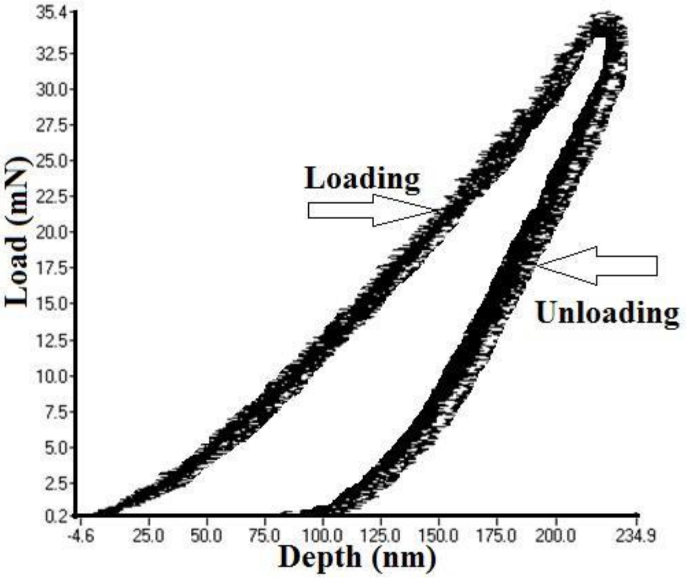
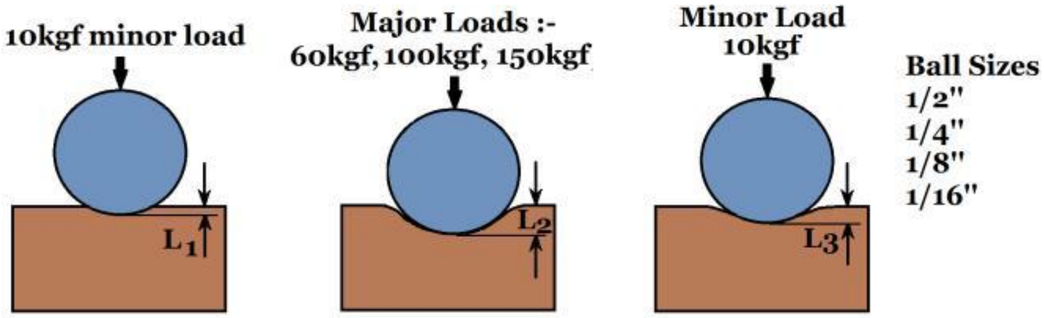


Figure 2: Schematic of Nanoindentation Plot between depth of penetration and applied load [13].

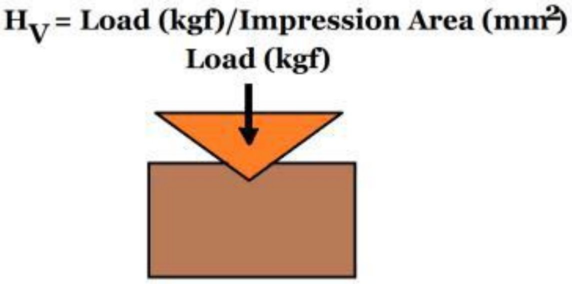
Conventional indentation instruments can give only hardness when known force is applying, it may measure by using projected area of the impression. To measure the internal hardness of the film indentation depth must below ten times than a film thickness otherwise the composite hardness influenced by the substrate will measure. In nano-indentation, penetrations of the indenter as a function of applied load were measured. Mechanical property of thin-film becomes very sensitive to the surface roughness, elastic modulus and hardness of material estimated by displacement vs resulting load curve [25,59]. To measure the size of the indents, nanoindentation method developed to record the displacement, time, stiffness, and load continuously throughout the indentation process developed by Soviet Union and applied in the early 1980s [58, 60 - 66]. An external load applied to the indenter tip during nanoindentation test shown in Fig.3 [58]. This intender made to push into the sample as the load applied and creates a nano scale impression on the sample. Conventional indentation test perform by pressing a tip to the sample of known geometry and fixed load, at last created indentation area will measure.

Rockwell, Vickers, and the Knoop test used to measure the hardness. Rockwell hardness test perform by pushing a ball with minor load, a major load, again minor load into the sample and calculating the depth as L1, L2, L3. In Vickers hardness testing four-sided pyramid pushed into the sample with a known load. Indentation area measured optically and the hardness calculated as the load divided by area. Knoop indentation uses the same principal of hardness as the Vickers test, load divided by area, with one long diagonal and one short diagonal indenter geometry.

Interface between the film and substrate affected by many variables and it affects the elastic, plastic behaviour of film. This consideration must take into account when prepare a model to test the performances of thin-film and interface. Coated system can divided in many categories neglecting the effect of interface and depends on the elastic modulus (E) and yield strength (Y) [67-69].



(a) Rockwell Hardness



(b) Vicker Hardness

Figure 3: Schematic Diagram of Rockwell, Vickers, & Knoop Hardness Indentation methods [58]

Conclusion

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. 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 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. Nanomechanical behaviour of thin-film and surfaces has been largely studying during past years. Electronics industry also adapted the thin-film application in MEMS [70] devices. A nanomechanical property such as viscoelastic, temperature, physics and chemistry of surfaces is likely to grow in the near future for the biological sector. Thin film application includes microelectronics, optoelectronics industries, telecommunicating devices, wear resistance coating, sensors, decorative coating, biotechnology, and energy conservation. In nanomechanical tests conducted with small mass and light load condition, where stress is negligible and mechanical performance dominated by surface properties. This MEMS field helps to understand mechanical behavior of thin-film materials at nanoscale with deposition system divided in many categories neglecting the effect of interface and depends on the elastic modulus and yield strength

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