DESIGN, FABRICATION AND MECHANICAL ISSUES RELATING TO THE USE OF MICRO-ENGINEERED DEVICES IN FUTURE GUIDED WEAPONS

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Abstract

The use of Micro-Engineered devices has been cited as a route to smaller, lighter, higher performance sub-systems for future guided weapons. This paper reviews the reasons for silicon Micro-Engineered structures being eminently suited to these applications. Materials properties and fabrication techniques are described which allow the manufacture of devices for the particular environmental and performance requirements of guided weapons. A particular development has been the manufacture of devices using bulk single crystal silicon and the Advanced Silicon Etch (ASE) or Deep Silicon Reactive Ion Etch (D-RIE) process. This allows great design flexibility (almost complete freedom in x and y), high accuracy (limited by the lithography), and unlike older technologies the fabricator can deliver what the designer asked for!

These features are compared to micro-engineered devices that are in commercial production and the differences discussed in both engineering and commercial terms. In particular some of the design features used to achieve high sensitivity, straightforward fabrication and a high degree of mechanical ruggedness are compared. The design and

fabrication technology is now largely mature and in place. We now need to see more devices taken from the laboratory demonstrator or proof of principle status to full evaluation in a realistic environment.

1. Introduction

Silicon Micro-Engineered devices are often cited as a key technology for the production of future sensors and actuators. In particular it is suggested that they offer:-

- Smaller size
- Lighter
- Cheaper
- Lower power
- Higher reliability
- Increased levels of integration (on board electronics, self test)
- Multi-functional

This paper is intended to show that when micro-engineering techniques are applied to niche market sectors (such as guided weapons, or indeed the Aerospace and Defence sector as a whole) there are commercial and technical reasons why some of these claims may be unfounded.

However some fabrication methods genuinely show distinct advantage over other technologies. An understanding of these issues will enable Guided Weapons engineers to pick appropriate technologies in terms of cost and performance for their particular application.

The applications are numerous, but obvious examples include:-

- Accelerometers
- Gyroscopes
- IMUs
- Pressure/altitude
- Fuzing & Arming
- Optical (IR & Vis) components
- RF components
- Air-data sensors
- Flight control surfaces
- E/O Sensors
- HUMS

This discussion begins with looking at the advantages and disadvantages of several micro-engineering technologies. The discussion is then extended to the mechanical properties of the materials themselves and some of their particular strengths and weaknesses. Finally this will be discussed along with commercial considerations to develop a strategy for introducing micro-engineered components into future guided weapons systems

2. Micro-Engineering Technologies

Four major classes of Micro-Engineering technologies will be discussed together the generic packaging issues associated with all sensors:-

- Wet Anisotropic Etched Bulk Silicon
- Dry Etched (D-RIE) Bulk Silicon
- Poly-silicon Surface Micro-Engineering
- Electro-deposited Materials

2.1 Wet Anisotropic Etching of Bulk Silicon

This is the most established of the techniques. It is based on the different wet etch rates of the different crystallographic planes in the silicon cubic crystal system (fig 1). Typically the three principle crystal planes ({100};{110};{111}) etch in a ratio of 400:200:1. Examples of the generic structures that can be produced by this technique are; membranes, cantilevers, seismic masses. Fig 2 shows the building blocks of common sensors which can be realised.

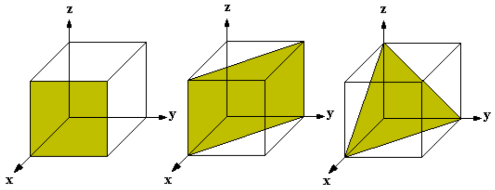

Fig 1. Major Crystal Planes in Silicon.

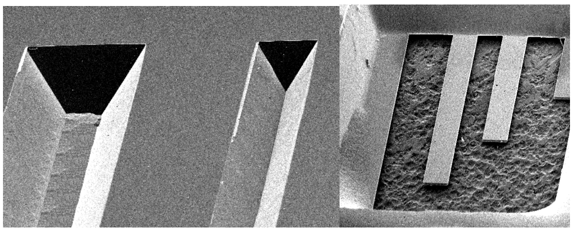

Fig 2. Examples of Anisotropic Wet Etched Structures.

However, the restrictions imposed by the crystallography of the single crystal silicon give rise to huge constraints in the structures that can be produced. This is particularly true when compensating for the complex etch fronts that develop at internal corners [ref. 1,2]. A consequence of these crystallography dependant complications is that the desired structures are not easy to predict and for sensors with performance critically dependant on the detailed mechanical behaviour (accelerometers and gyroscopes) the performance is never going to be as good as simple FEM models would predict.

2.2 Dry Etched (D-RIE) Bulk Silicon

This plasma based process allows the rapid etching of silicon, with vertical walls to any shape that can be defined by photo-resist at thickness up to, and beyond the full thickness of a standard 100mm silicon wafer. High aspect ratio trenches can be achieved which lend themselves to, for example, high device packing densities, or sensitive capacitor plates for electrostatic displacement or sensing. High aspect ratio structures allow the de-coupling of sensitive low compliance structures in the x –

y plane from very stiff structures in the z or thickness direction. Thus sensitivity and ruggedness or low cross-axis sensitivity is more easily achievable. Furthermore integration with electronics has been demonstrated. The development of this process has been the holy grail of the silicon micro-engineering community for in excess of a decade - BAE SYSTEMS knew it required this process in order to realise silicon ring gyros long before the original Bosch patent on the process was published [ref 3]. Since then three or four plasma etch equipment suppliers have commercialised the process. In particular Surface Technology Systems (STS), Newport, UK, have established themselves as the leading supplier of the equipment to both the R & D and increasingly for production manufacturers of sensors. Examples of the process are shown in fig. 3. Notice the smooth vertical walls and freedom to create curved structures irrespective of crystallography.

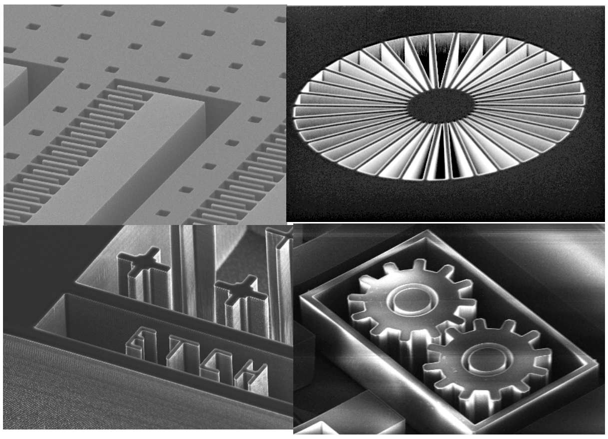

Fig 3. Examples of Si D-RIE etched structures.

Despite its recent rise to prominence there are already commercial devices available using the D-RIE process as its main sensor definition step. These include the BAE SYSTEMS – Sumitomo produced Silicon Vibrating Structure Gyro (Si-VSG), which is now in volume production.

2.3 Poly-Silicon Surface Micro-Engineering

In this process mechanical or other sensor elements are dry etched from a relatively thin deposited film of polycrystalline silicon. The structures are then freed by etching away a sacrificial layer (typically silicon dioxide) from beneath the poly-silicon (fig 4). The dry-etch definition of the layer structure gives a greater degree of freedom to the sensor designer than the bulk silicon anisotropic wet etch technique [ref 4,5].

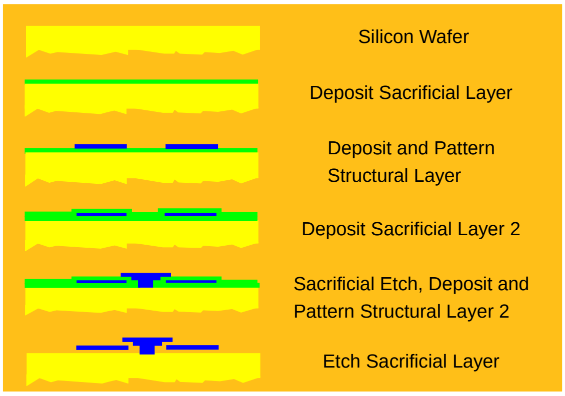

Fig 4. Schematic of poly-silicon surface micromachining process flow.

However this is only true of in-plane (x-y) features. The technique is still limited in the variety of thicknesses of both poly-silicon and silicon dioxide layers that can be deposited (in the range 1 to many 10's of microns).

This limitation gives rise to a fundamental limit in sensitivity to a class of device of particular importance to guided weapons engineers – accelerometers. For these devices a compromise in performance has to be met between range, sensitivity and bandwidth. This can be illustrated for a simple cantilever accelerometer structure by:-

Sensitivity (s)

$$s \propto \frac{ml^3}{EI}$$

Bandwidth (BW)

$$BW \propto \sqrt{\frac{EI}{ml^3}}$$

where
m – mass
l – length of cantilever

E – Youngs modulus
I – 2nd moment of inertia and is given by

$$I = \frac{bt^3}{12}$$

where b – width cantilever
t – thickness cantilever

Range – for an open loop accelerometer, this is limited by the range over which the compliance and transduction method is linear (or linearisable).

Thus there is always a compromise between range, bandwidth and sensitivity. Stiff suspensions give range and bandwidth, whilst compliant suspensions give high sensitivity. Greater mass gives increased sensitivity, but reduced bandwidth. Thus for a particular geometric compliance the poly-silicon surface micro-machined device cannot satisfy the sensitivity criteria, because of its low mass. In this respect the bulk silicon devices will always be a better solution. Further improvement at the expense of more complex electronics and mechanical vulnerability (see section 4) can be achieved by the use of a closed loop force feedback system. A further limitation of the thin layer structure of surface micro-machined devices is the inability to make very stiff structures in the thickness direction. This also has implications for ruggedness and cross axis sensitivity.

Despite these limitations poly-silicon processes have reached a high degree of commercial maturity and have proved the easiest to integrate with standard CMOS processing for those devices where it is desirable to integrate the sensor element and electronics together since they both have similar yield drivers. Indeed the most widely cited example of a micro-engineered device – the ADXL range of Accelerometers from Analog Devices is fabricated with this technology.

2.4 Electro-Deposited Materials

Various lithographic techniques have been used to produce moulds [ref. 6,7] from which electro-deposited materials (principally nickel alloys) can be built up into high aspect ratio structures. The process is shown schematically in fig 5.

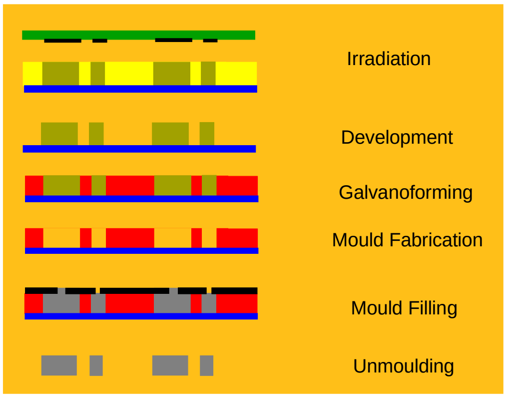

Fig 5. Schematic process flow to realise electro-deposited structures.

The utilisation of this method comes down to which method is used for defining the structure. The LIGA technique is notoriously expensive, but some of the advanced optical techniques may give rise to cost effective solutions. It is probably true that the technique offers no advantage over poly-silicon processes for devices of interest to Guided Weapons engineers, except in applications where a metallic conductor give advantage over a semi-conducting material, such as electromagnetic devices where inductors and solenoid structures are required.

2.5 Packaging

The packaging of the micro-engineered sensor or actuator is arguably the key element in the successful exploitation of micro-engineering technology. Not only can it contribute up to 80% of the cost of the sensor, but the complex combinations of materials with thermal and mechanical mismatch often limit the sensitivity of the device. It is often stated, but rarely practised that packaging issues should be designed in at proof of concept stage rather than a discrete step which can be carried out at a later date to make the device compatible with volume production.

Current commercial micro-engineered devices, particularly as one moves to niche applications smaller volume devices often have disappointingly large metallic packages around them, throwing away the initially perceived advantage of a very small silicon die. Not only can packaging issues be solved more elegantly by resolving them at the silicon level, but by carrying out much of the processing at wafer level, rather than individual die, processing costs will fall dramatically.

2.6 General Concluding Comments on Fabrication Routes

There is a vast and expanding literature of devices and novel fabrication routes [e.g. ref 8,9] using the above and more techniques. Critical examination of the state of maturity shows that the majority of the academic sensor papers fall into the "one off" laboratory demonstrator category, often with complex, difficult to control processes. The key to commercial success is simple robust processes that are easily transferred to a production environment.

3. Materials Properties

In discussing the fabrication techniques available we have seen that some are appropriate to low cost devices (bulk wet etched), some to high performance devices (bulk D-RIE etched) and some to very low cost, low performance devices with on board electronics (surface micro-machined poly-silicon devices). This section discusses the additional benefits and disadvantages of the various techniques by virtue of the sensor or actuator's intrinsic material properties. This will allow the guided weapons engineer to further down-select an appropriate micro-engineering technology.

Although silicon is not the only material used for micro-engineered devices, it is the most widely used because of the maturity and variety of processing techniques. However a comparison of its mechanical properties compared to several common engineering materials is a useful exercise:-

Table 1

Material	Yield Strength MPa	Youngs Modulus GPa	Elastic Range	Quality Factor Q
Silicon (single crystal) {111} {110} {100}	7000	130 160 190	0.6% >1.5% >1.5%	High
Poly-Silicon		130-160		Modest
Electro Dep Ni	60-400	170-200	0.3%	Modest/ poor
Mild Steels	100-500	210	0.2%	
Aluminium (2.xxx series)	400-550	70	0.2%	poor
Carbon Fibre	3,800	220	1.7%	

Note that single crystal silicon is a remarkably good mechanical material – stronger than many steels and aluminium alloys.

Even more important from the operation of a sensor point of view is that it has a large elastic range and no hysteresis in the stress - strain curve. Poly-silicon on the other hand has poorer mechanical properties as a result of its grain boundaries. Other micro-engineering materials such as electro-deposited nickel also fall short of the exceptional materials properties of single crystal materials. Of course one has to respect the fact that unlike ductile metals silicon fails by brittle fracture. This dramatic failure mode should not be of concern as long as precautions are taken to ensure that the structure required cannot exceed the elastic limit (see below). This is perhaps seen most dramatically in fig 6.

Thus as long as the design engineer can be assured that the structural elements will be constrained to well within the elastic limits, a successful device is likely to result. Of the previously discussed single crystal silicon fabrication routes, D-RIE achieves this most readily. Furthermore since the structure can be accurately predicted in advance, FEM modelling techniques can be used to predict not only sensor performance but also influence of environmental parameters (launch shocks, temperature excursions etc).

In the extreme, single crystal silicon could be used as a structural material in its own right. For example much has been said [ref 10] about micro flying vehicles, with overall dimensions of 6” and less, used for surveillance, targeting or other tactical applications. At this scale it is a considerable technical challenge to produce a vehicle with a mass <100g, capable of carrying a useful payload. Not only does single crystal silicon offer the possibility of achieving this but its multi-functional properties lead to additional sensing, electronic and optical functions, for no extra weight penalty.

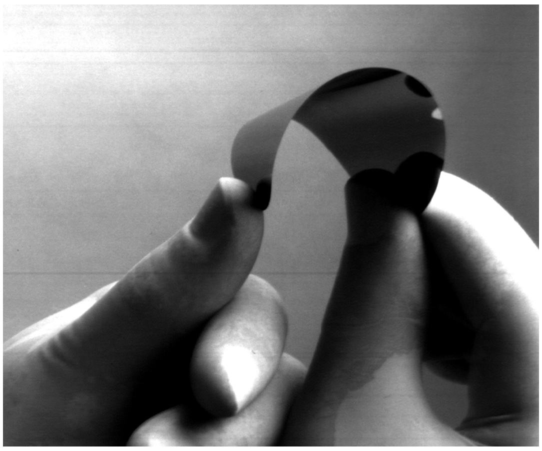

Fig 6. Silicon as a flexible structural material (Photo courtesy Virginia semiconductors inc.).

4. Features Relating to Particular Fabrication/Material Combinations

After discussing general issues relating to fabrication and materials properties, this section picks out a few rather specific “tricks of the trade”, discusses where these features are important and what benefit they bring to the device performance.

4.1 Stiction

The cohesive forces between two smooth flat surfaces that are wetted during fabrication, or subsequently make contact in service can be large enough to cause them to stick together permanently- a phenomenon known as stiction. This is a particular problem when layers are separated by small gaps (such as that created by removal of the sacrificial layer in poly-silicon surface micro-machining). However it can also occur in other fabrication schemes, particularly when very compliant structures are required. In the case of accelerometers a high compliance is desired for sensitivity and so methods are needed to overcome these forces or prevent the smooth parallel surfaces from coming together. Typically in the z (thickness) direction the D-RIE process is able to etch deep enough to produce a structure too stiff for stiction to be a problem (c.f. poly-silicon processes). However in the x-y directions anti-stiction stops are required. A series of cantilevers produced by the D-RIE process are shown in fig 7, with small stops. The SEM micrograph clearly shows that after a wet oxide etch release process the stops are effective at eliminating stiction.

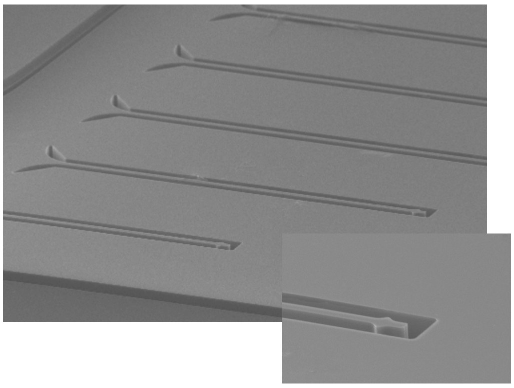

Fig 7. Anti-stiction stops.

4.2 Over Range Stops (Bump stops)

Simple physical stops are all that is required to prevent silicon being strained outside its elastic limit. For in plane motion this can be achieved by appropriate selection of gap sizes, albeit with consideration given to stiction as discussed above. Out of plane motion can also be prevented, but the use of additional capping layers above or below the plane of the sensor are best avoided, because of processing costs unless required for other reasons (e.g. damping).

4.3 Damping

Despite the high degree of control over the mechanical structure it is often desirable to modify the damping behaviour of a vibrating system. One commonly used technique is to rely on squeeze film damping of a gas or liquid around a restricted gap. Once again the D-RIE process offers high aspect ratio narrow gap trenches in which effective squeeze film damping can be achieved

4.4 Stress Relief

The crystallographic limitations of wet anisotropic etched structures have been shown to give poorer mechanical performance than expected [ref 11]. Furthermore this has been shown to be attributable to locally high stresses at the corner regions of {100} and {111} crystal planes. Subsequent isotropic etching to stress relief and radius the sharp corners was shown to improve the mechanical properties.
The complete design freedom in the D-RIE process allows rounded corners to be placed on all areas that may be expected to have stress enhancement. Fig 8 shows how this has been implemented on the compliant legs used to support the Si-VSG gyroscope.

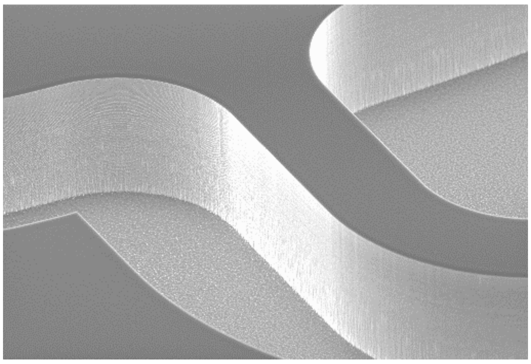

Fig 8. Si-VSG Leg structure.

5. Commercial Considerations

5.1 Size of Market

A key advantage that is always given for micro-engineering technology is that it offers low cost devices because of the batch processing of large volumes. One has to recognise that this is true only when the market size for the particular sensor is in the millions/annum. A cursory look at the commercially successful micro-engineering devices that are in the market place today illustrates this point:-

- Airbag accelerometers
- Automotive Gyros for ABS
- Disposable Medical Pressure sensors
- Ink Jet Print Heads

Guided Weapons engineers often require sensors in the 100 to 10,000 device/annum level. This is a difficult market volume to address in isolation. British Aerospace have recognised this factor and deliberately added automotive and commercial applications as the principal markets for the Si-VSG ring gyroscope, but recognise the importance of the military market too.
If we now turn to the more specialised markets a general trend between volume and performance can be seen schematically in fig. 9 below:-

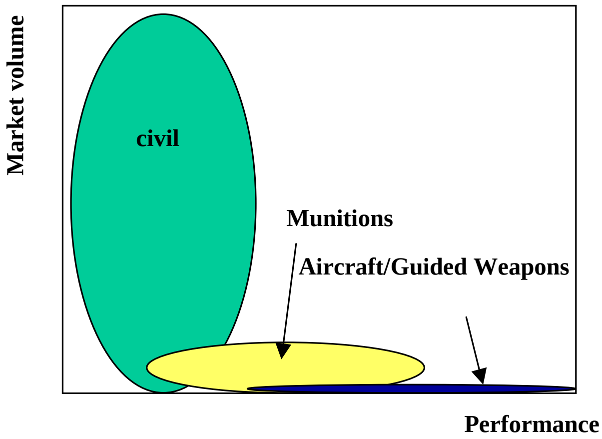

Fig 9. Market volume/performance.

It should not be interpreted that very high performance devices produced in small quantities will not offer commercial benefit, but that there is a price to pay. As an extreme example BAE SYSTEMS produce a surface micromachined device with custom integrated electronics that generates a real time moving infra-red scenes. This hand crafted device is used for hardware in the loop evaluation of IRseeker based missiles. Despite its high development and production costs (~£1M, it still provides the company with a way of testing guided missiles earlier in their development programme than previously possible. It also offers many tens of millions of pounds direct cost savings because of the vastly reduced live firing programme required.

Finally at the other end of scale cost constraints may force the use of civil, commercial off the shelf devices. It is important to have a thorough understanding of the manufacturing and performance issues to use these devices effectively.

6. Conclusions

Micro-engineering technology offers the guided weapons engineer with a huge range of potential devices that offer potential cost and performance improvements.

A clear understanding of the fabrication processes, materials properties and device performance is critical to the selection of appropriate technology

The specialised requirements of future guided weapons will necessitate a combination of procurement of commercial devices and development of application specific micro-engineered components.

Of all the fabrication technologies available DRIE of bulk single crystal silicon offers the lowest risk route to bespoke devices.

The British Aerospace exploitation route of the Si-VSG silicon gyro is a good model for dual use technology. Without establishing a civil market, devices would not be available for military use.

References

[1] X W Wu and W H Ko, *Compensating Corner Undercutting in Anisotropic Etching of (100) Silicon*, Sensors and Actuators, 18, 1989, p207-215.

[2] B Puers and W Sansen, *Compensation Structures for Convex Corner Micromachining in Silicon*, Sensors and Actuators, A21-23, 1990, pp 1036,1041.

[3] J Bhardwaj et. al**.**, *On Inductively Coupled Plasma Etching and HARMST*, HARMST '99, 13-15 June, 1999, pp18-21.

[4]H Dudaicevs et. al., *Surface micromachined pressure sensors with integrated CMOS read-out electronics*, Sensors and Actuators A, vol 43, 1994, pp157.

[5] F Chollet et. al., *Micromachined Shutter and Low-Voltage Electronics for Optical Displacement/Acceleration Sensing*, Transducers '99, June 7-10, 1999, pp1526-1529.

[6] V Saile, *Research and Development in High Aspect Ratio Microstructure Technology at Forschungszentrum Karlsruhe*, HARMST '99, 13-15 June, 1999, pp30-31.

[7] L J Guerin et. al., *High Aspect Ratio Planar coils embedded in SU8 photoepoxy for MEMS applications*, Proc. Eurosensors XII, Sept. 1998, Southampton, pp11-14.

[8] e.g *Transducers '99*, The 10th International Conference on Solid-State Sensors and Actuators, Sendai, Japan, June 7-10, 1999.

[9] IEEE International *MEMS'99*, Twelfth IEEE International Conference on Micro Electro Mechanical Systems, Orlando, Florida, USA, Jan 17-21, 1999.

And Eurosensors XII, Institute of Physics, 12th European Conference on Solid-State Transducers and the 9th UK Conference on Sensors and their Applications, Southampton, 13-16 Sept., 1998.

[10]http:/www.darpa.mil/ARPATech-96/transcripts/francis.html

[11] F. Pourahmadi, D. Gee, K. Petersen, *The Effect of Corner Radius of Curvature on the Mechanical Strength of Micro-machined Single Crystal Silicon Structures***,** IEEE 1991, vol 91CH2817-5/91, page 197