Explosure of Micro Electromechanical Systems (MEMS) based applications

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ABSTRACT

Over the past two decades, several advances have been made in micro machined sensors and actuators. Thesemicrosensors are used in almost every possible sensing modality including temperature, pressure, inertial forces, chemical species, magnetic fields, radiation etc. At this time, piezoelectric aluminum-nitride-based Film Bulk Acoustic Resonators (FBAR) has already been successfully commercialized in many applications. Future innovations and improvements in inertial sensors for navigation, high-frequency crystal oscillators and filters for wireless applications, microactuators for RF applications, chip-scale chemical analysis systems and countless other applications hinge upon the successful miniaturization of components and integration of piezoelectrics and metals into these systems. In this paper, a comprehensive study of micro electro mechanical systems, materials, fabrication technology and various applications of MEMS will be explained.

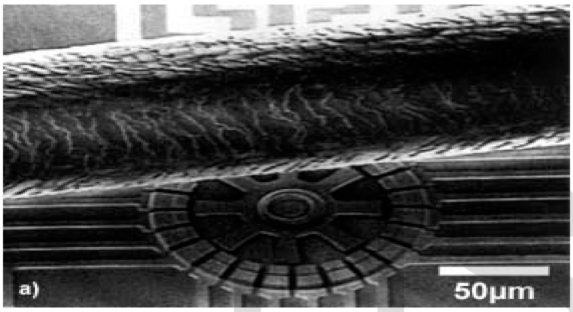
Key words: MEMS, Materials, Fabrication, Sensors and Actuators.

1. INTRODUCTION:

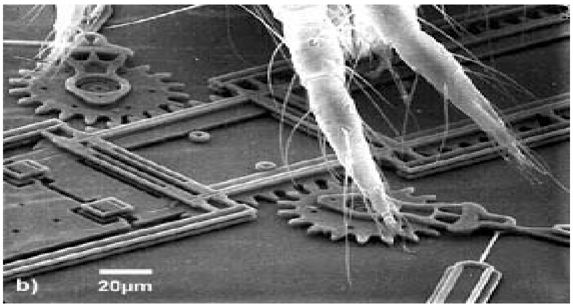
Definition of MEMS:

Micro-electromechanical systems (MEMS) is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components. They arefabricated using integrated circuit (IC) batch processing techniques and can range in size from a few micrometers to millimetres. These devices (or systems) have the ability to sense,control and actuate on the micro scale, and generate effects on the macro scale.While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable (and perhaps most interesting) elements are the micro sensors and microactuators. Micro sensors and microactuators are appropriately categorized as “transducers”, which are defined as devices that convert energy from one form to another. In the case of micro sensors, the device typically converts a measured mechanical signal into an electrical signal.

Microsensorsdetect changes in the system’s environment by measuring mechanical, thermal, magnetic, chemical or electromagnetic information or phenomena. Microelectronics processes this information and signals the microactuators to react and create some form of changes to the environment. MEMS devices are very small; their components are usually microscopic. Levers, gears, pistons, as well as motors and even steam engines have all been fabricated by MEMS (Figure 2). However, MEMS is not just about the miniaturization of mechanical components or making things out of silicon (in fact, the term MEMS is actually misleading as many micro machined devices are not mechanical in any sense). MEMS is a manufacturing technology; a paradigm for designing and creating complex mechanical devices and systems as well as their integrated electronics using batch fabrication techniques.



(a) A MEMS silicon motor together with a strand of human hair



(b) the legs of a spider mite standing on gears from a micro-engine

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 micro motor fabrication in the late eighties and early nineties[3], and now myriad devices for various applications. MEMS are 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 accomphlished 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[5]. 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 am exercise in optimization. In fact, material selection is usually dictated by the availability and case 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 put 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 enchanting 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.

2.MATERIALS FOR MEMS MANUFACTURING:

2. MEMS Materials

Requirements of a MEMS process flow are inclusion of one or more mechanical materials, unit processes to shape (micro machine) these materials and, in most cases, unit processes to release parts of the structural material fromother anchored materials. The choice of micromachining process usually starts with a specification of device dimensions and tolerances. Structures over 10 µm in thickness usually dictate bulk micromachining, while structures under 10 µm usually incorporate surface micromachining or hybrid bulk/surface micromachining. There are five main categories of micromechanical materials, as shown in Figure 2. The structural material and substrate material, which may be one in the same, must be able to survive the various process steps. Structural material properties of interest include Young's modulus, yield strength, density, residual stress and stress gradients, electrical and thermal conductivity and long-term stability of these properties. Spacer materials are usually completely or partially etched away to release the microstructure, and areoften called sacrificial materials because of this function. Spacer materials may also be used to make melds for structures. Surface materials may be used to protect the substrate or structural material from certain etching steps. Surface materials are also important for achieving electrical isolation. Active materials are incorporated on structures to exploit their special physical transduction characteristics. Probably every possible transduction mechanism has been explored in MEMS. Common transduction effects are silicon piezoresistance to measure stress, the piezoelectric effect in ZnO, PZT, AlN for both stress sensing and actuation, temperature coefficient of resistance and thermoelectric properties of silicon, aluminum and other conductors to measure temperature, and various magnetic materials to couple mechanically to magnetic fields.

Silicon

Silicon is the material used to create most integrated circuits used in consumer electronics in the modern world. The economies of scale, ready availability of cheap high-quality materials and ability to incorporate electronic functionality make silicon attractive for a wide variety of MEMS applications. Silicon also has significant advantages engendered through its material properties. In single crystal form, silicon is an almost perfect Hookean material, meaning that when it is flexed there is virtually no hysteresis and hence almost no energy dissipation. As well as making for highly repeatable motion, this also makes silicon very reliable as it suffers very little fatigue and can have service lifetimes in the range of billions to trillions of cycles without breaking.

Polymers

Even though the electronics industry provides an economy of scale for the silicon industry, crystalline silicon is still a complex and relatively expensive material to produce. Polymers on the other hand can be produced in huge volumes, with a great variety of material characteristics. MEMS devices can be made from polymers by processes such asinjectionmolding, embossing or stereo lithography and are especially well suited to microfluidic applications such as disposable blood testing cartridges.

Metals

Metals can also be used to create MEMS elements. While metals do not have some of the advantages displayed by silicon in terms of mechanical properties, when used within their limitations, metals can exhibit very high degrees of reliability. Metals can be deposited by electroplating, evaporation, and sputtering processes. Commonly used metals include gold, nickel, aluminium, copper, chromium, titanium, tungsten, platinum, and silver.

Ceramics

The nitrides of silicon, aluminium and titanium as well as silicon carbide and other ceramics are increasingly applied in MEMS fabrication due to advantageous combinations of material properties. AlN crystallizes in the quartzite structure and thus shows piezoelectric and piezoelectric properties enabling sensors, for instance, with sensitivity to normal and shear forces.[5] TiN, on the other hand, exhibits a high electrical conductivity and large elastic modulus allowing to realize electrostatic MEMS actuation schemes with ultrathin membranes.[6] Moreover, the high resistance of TiN against biocorrosion qualifies the material for applications in biogenic environments and in biosensors.

Materials for Micromachining

Substrates

The most common substrate material for micromachining is silicon. It has been successful inthe microelectronics industry and will continue to be in areas of miniaturization for several

Reasons:

i) silicon is abundant, inexpensive, and can be processed to unparalleled purity

ii) Silicon’s ability to be deposited in thin films is very amenable to MEMS

iii) High definition and reproduction of silicon device shapes using photolithography areperfect for high levels of MEMS precision

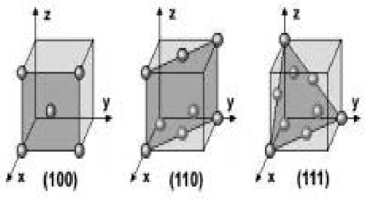
iv) Silicon microelectronics circuits are batch fabricated (a silicon wafer contains

hundreds of identical chips not just one)

Other crystalline semiconductors including germanium (Ge) and gallium arsenide (GaAs) are used as substrate materials due to similar inherent features, but silicon is distinguished from

other semiconductors in that it can be readily oxidized to form a chemically inert andelectrically insulating surface layer of SiO2 on exposure to steam.The homogeneous crystal structure of silicon gives it the electrical properties needed in

Microelectronic circuits, but in this form silicon also has desirable mechanical properties.Silicon forms the same type of crystal structure as diamond, and although the interatomicbonds are much weaker, it is harder than most metals. In addition, it is surprisingly resistantto mechanical stress, having a higher elastic limit than steel in both tension and compression.Single crystal silicon also remains strong under repeated cycles of tension and compression.The crystalline orientation of silicon is important in the fabrication of MEMS devices becausesome of the etchants used attack the crystal at different rates in different directions



Low crystallographic index planes of silicon

Additive Films and Materials

The range of additive films and materials for MEMS devices is much larger than the types ofpossible substrates and includes conductors, semiconductors and insulators such as:

☐☐ silicon- single crystal, polycrystalline and amorphous

☐☐ silicon compounds (SixNy, SiO2, SiC etc.)

☐☐ metals and metallic compounds (Au, Cu, Al, ZnO, GaAs, IrOx, CdS)

☐☐ ceramics (Al203 and more complex ceramic compounds)

☐☐ organics (diamond, polymers, enzymes, antibodies, DNA etc.)

3. FABRICATION:

Bulk Micromachining

Bulk micromachining involves the removal of part of the bulk substrate. It is a subtractiveprocess that uses wet anisotropic etching or a dry etching method such as reactive ion etching(RIE), to create large pits, grooves and channels. Materials typically used for wet etching include silicon and quartz, while dry etching is typically used with silicon, metals, plasticsand ceramics.

Wet Etching

Wet etching describes the removal of material through the immersion of a material (typically a silicon wafer) in a liquid bath of a chemical etchant. These etchants can be isotropic oranisotropic.Isotropic etchants etch the material at the same rate in all directions, and consequently removematerial under the etch masks at the same rate as they etch through the material; this is knownas undercutting (Figure 19 a and b). The most common form of isotropic silicon etch is HNA,which comprises a mixture of hydrofluoric acid (HF), nitric acid (HNO3) and acetic acid(CH3COOH). Isotropic etchants are limited by the geometry of the structure to be etched.

Etch rates can slow down and in some cases (for example, in deep and narrow channels) theycan stop due to diffusion limiting factors. However, this effect can be minimized by agitationof the etchant, resulting in structures with near perfect and rounded surfaces

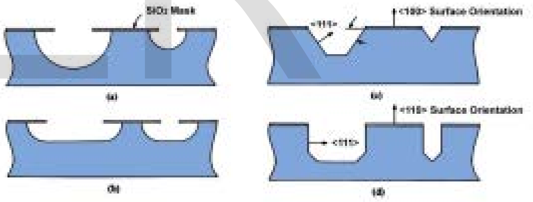


Figure. Isotropic etching with (a) and without (b)

Agitation and anisotropic wet etching of (100) and (110) Silicon (c and d respectively)

Anisotropic etchants etch faster in a preferred direction. Potassium hydroxide (KOH) is themost common anisotropic etchant as it is relatively safe to use. Structures formed in thesubstrate are dependent on the crystal orientation of the substrate or wafer. Most suchanisotropic etchants progress rapidly in the crystal direction perpendicular to the (110) plane and less rapidly in the direction perpendicular to the (100) plane. The direction perpendicularto the (111) plane etches very slowly if at all. Figures 19c and 19d shows examples ofanisotropic etching in (100) and (110) silicon. Silicon wafers, originally cut from a largeingot of silicon grown from single seed silicon, are cut according to the crystallographicplane. They can be supplied in terms of the orientation of the surface plane.Dopant levels within the substrate can affect the etch rate by KOH, and if levels are highenough, can effectively stop it. Boron is one such dopant and is implanted into the silicon bya diffusion process. This can be used to selectively etch regions in the silicon leaving dopedareas unaffected.

4. MEMSCOMPENENTS:

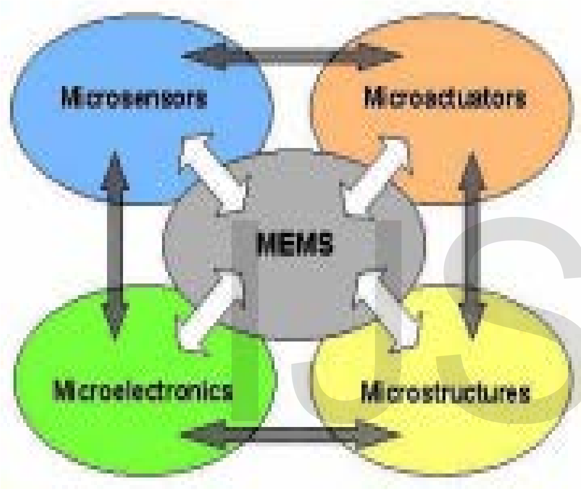


Figure 1.Schematic illustration of MEMS components.

MEMS Transducers

Micro sensors and micro actuators are at the very core of a MEMS device or system. A micro sensor detects changes in the system's environment; an 'intelligent' part processes theinformation detected by the sensor and makes a decision in the form of a signal; and microactuators acts on this signal to create some form of changes in the environment. Microelectronic components make up most of the intelligent part of the device and, as an Established technology will not be discussed here.

Sensors and actuators are broadly termed transducers and are essentially devices that convertone form of energy into another. Many of the MEMS sensors and actuators described in thissection have been developed within the microelectronics industry and do not all involve anyspecial micromachining techniques; they are based on conventional integrated circuits that,through inherent However, many of these can beenhanced by the use of MEMS.Basic MEMS mechanisms and structures consist of both in-plane and out-of-planemechanisms as well as structural members to couple energy between the actuator and sensorsas well as with the physical interface of a mechanical system. Mechanisms such as joints,linkages, gears and hinges are very typical.This section concentrates on the phenomena that can be sensed or acted upon with MEMSdevices with a brief description of the basic sensing and actuation mechanisms. It isimportant to note that although these devices are mechanical and have been categorized interms of their sensing domain (e.g. thermal, chemical, radiation), there are many overlaps, andforms of mechanical transducer can be commonly found as intermediate mechanisms in otherdevices.

Mechanical Transducers

4.1.1 Mechanical Sensors

There is a tremendous variety of direct mechanical sensors that have been or could be Micro machined depending on their sensing mechanism (usually piezoresistive, piezoelectricor capacitive) and the parameters sensed (typically strain, force and displacement).

i) Piezoresistive sensors

As a result of the piezoresistive effect (defined as the change in resistivity of the material withapplied strain), changes in gauge dimension result in proportional changes in resistance in thesensor. The piezoresistive effect in semiconductors is considerably higher than in traditionalmetals, making silicon an excellent strain sensor. MEMS piezoresistors are readily Manufactured using bulk silicon doped with p-type or n-type impurities.

ii) Piezoelectric sensors

Piezoelectric sensors utilize the piezoelectric effect in which an applied strain (or force) on apiezoelectric crystal results in a potential difference across the crystal. Similarly, if the crystalis subjected to a potential difference, a displacement, or strain, is produced. The effect can beused to sense mechanical stress (i.e. displacement) and as an actuation mechanism, althoughdisplacements are small even for large voltages. Common piezoelectric materials used forMEMS applications include quartz, lead zirconatetitanate (PZT), polyvinylidene fluoride (PVDF) and ZnO, PVDF and ZnO being the most common. Silicon is not piezoelectric;hence a thin film of a suitable material must be deposited on the devices.

iii) Capacitive sensors

Capacitive (or electrostatic) sensing is one of the most important (and widely used) precisionsensing mechanisms and includes one or more fixed conducting plates with one or moremoving conducting plates. Capacitive sensing relies on the basic parallel-plate capacitor

Equation shown below. As capacitance is inversely proportional to the distance between theplates, sensing of very small displacements is extremely accurate.

iv) Resonant sensors

MEMS resonant sensors consist of micro machined beams or bridges which are driven tovibrate at their resonant frequency. They can be attached to membranes or designed to adhereto a particular substance (as in the case of a biosensor). Movement of the membrane orincreased build-up of the binding substance will affect the resonant frequency and can be monitored using implanted piezoresistors.

5.Applications:

Today ,high volume MEMS can be found in a diversity of application across multiple marets (Table 1)

Table 1.Applications of MEMS

Automotive	**Electronics**	**Medical**	**Communication**	**Defence**
Internal navigation sensors	**Disk drive heads**	**Blood pressure sensor**	**Fibre-optic network components**	**Munitions guidance**
Air conditioning compressor sensor	**Inkjet printer heads**	**Muscle stimulators & drug delivery systems**	**RF Relays, switches and filters**	**Surveilllance**
Brake force sensors & suspension control accelerometers	**Projection screen televisions**	**Implanted pressure sensors**	**Projection displays in portable communications devices and instrumentation**	**Aming systems**
Fuel level and vapour pressuresensors	**Earth quake sensors**	**Prosthetics**	**Voltage controlled oscillators (VCOS)**	**Embedded sensors**

Air bag sensors	**Avionics pressure**	**Miniature analytical instruments**	**Splitters and couplers**	**Data storage**
“Intelligent” tyres	**Mass data storage systems**	**Pacemakers**	**Tuneable lasers**	**Aircraft control**

New MEMS Applications

The experience gained from these early MEMS applications has made it an enablingtechnology for new biomedical applications (often referred to as bioMEMS) and wireless communications comprised of both optical, also referred to as micro-optoelectromechanicalsystems (MOEMS), and radio frequency (RF) MEMS.

BioMEMS

Over the past few years some highly innovative products have emerged from bioMEMScompanies for revolutionary applications that support major societal issues including DNAsequencing, drug discovery, and water and environmental monitoring. The technologyfocuses on microfluidic systems as well as chemical testing and processing and has enableddevices and applications such as ‘lab-on-a-chip’, chemical sensors, flow controllers, micronozzles and micro valves to be produced. Although many devices are still underdevelopment, microfluidic systems typically contain silicon micro machined pumps, flow sensors and chemical sensors. They enable fast and relatively convenient manipulation andanalysis of small volumes of liquids, an area of particular interest in home-based medicalapplications where patients can use devices to monitor their own conditions, such as bloodand urine analysis.

One example of a new bioMEMS device is the microtitreplate on which a number of cavitiescan be simultaneously filled accurately and repeatably by capillary force (Figure 11a). This isa relatively simple MEMS product in the form of a piece of plastic with high-aspect-ratiomicromachinedmicrochannels and is classified as a ‘lab-on-a-chip’ product. Its dimensions are only 20 mm x 37 mm x 3 mm and enables automatic filling of 96 micro wells by the use of capillary action.

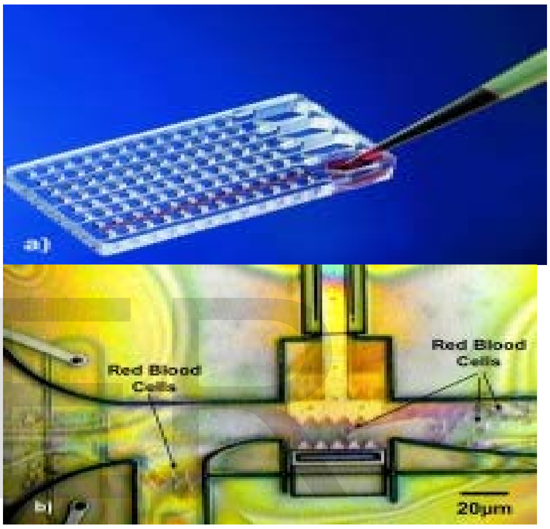


Figure 1 (a) Micromachinedmicrotitreplate with 96 cavities filled by capillary

force and (b) a bioMEMS device actuated with ‘microteeth’ to trap, hold and release single red blood cells (unharmed). The little balls in the channels are red blood cells

Future lab-on-a-chip technology may include implantable ‘pharmacy-on-a-chip’ devices tocarefully release drugs into the body from tiny chambers embedded in a MEMS device,eliminating the need for needles or injections. The delivery of insulin is one such application,as is the delivery of hormones, chemotherapy drugs and painkillers. First generation devicesare being developed which release their medication upon signals from an outside source,wired through the skin. Proposed second generation devices may be wireless and thirdgeneration MEMS chips could interact with MEMS sensors embedded in the body to respondto the body's own internal signals.

One of the most recent MEMS microfluidic devices to emerge from development laboratories Incorporates a 'Pac-Man'-like microstructure that interacts with red blood cells . The device from Sandia National Laboratories, U.S.A, contains silicon microteeth that openand close like jaws trapping and releasing a single red blood cell unharmed as it is pumped through a 20 µm channel. The ultimate goal of this device is to puncture cells and inject them with DNA, proteins, or pharmaceuticals to counter biological or chemical attacks, geneimbalances and natural bacterial or viral infections.

MOEMS

Optical communications has emerged as the only practical means to address the networkscaling issues created by the tremendous growth in data traffic caused by the rapid rise of theInternet. Current routing technology slows the information (or bit) flow by transformingoptical signals into electronic information and then back into light before redirecting it. Alloptical networks offer far superior throughput capabilities and performance over traditionalelectronic systems.The most significant MOEMS device products include waveguides, optical switches, crossconnects, multiplexers, filters, modulators, detectors, attenuators and equalizers. Their small size, low cost, low power consumption, mechanical durability, high accuracy, high switchingdensity and low cost batch processing of these MEMS-based devices make them a perfectsolution to the problems of the control and switching of optical signals in telephone networks.An example of a MEMS optical connect is shown in Figure 12. Here a network of 256MEMS micromirrors route information in the form of photons (the elementary particle thatcorresponds to an electromagnetic wave) to and from any of 256 input/output optical fibres.

Figure 3 :A MEMS optical cross connect consisting of an array of microscopic mirrors, each the size of a pin head and able to tilt in various directions to steer light

MEMS fabrication processes have reached the stage where mass manufacture of such devicesis now practical. A typical optical switch can cost over $1000, but using MEMS, the samelevel of functionality can be achieved for less than a dollar. Agree Systems (previously known as the microelectronics division of Lucent Technologies), Corning, JDS Uniphase andSycamore Networks are some of the leading companies in this field.

RF MEMS

RF MEMS is one of the fastest growing areas in commercial MEMS technology. RF MEMSare designed specifically for electronics in mobile phones and other wireless communicationapplications such as radar, global positioning satellite systems (GPS) and steerable antennae.MEMS has enabled the performance, reliability and function of these devices to be increasedwhile driving down their size and cost at the same time

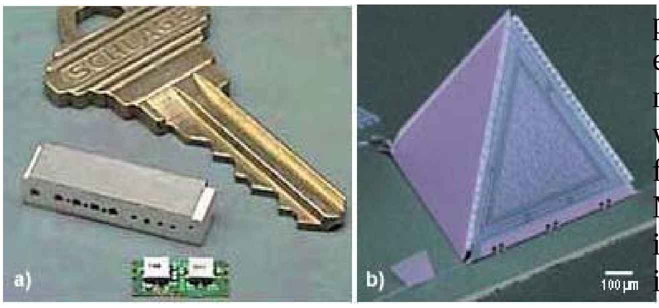


Figure 4: (a) A miniature acoustic resonator, shown in theforeground, is one-fifth the size of a traditional component used inmobile phones and other wireless communications devices [22],and (b) on-chip micro-microphones may make it possible to build radios on a chip The technology includes circuit tuning elements (capacitors/inductors, resonators, filters,microphones and switches). These low-loss ultra-miniature and highly integrative RFfunctions can and will eventually replace classical RF elements and enable a new generationof RF devices. As it can be seen today, if RF MEMS components continue to replacetraditional components in today's mobile phones, then phones could become extremely small(the size of wristwatch is not too far away), require little battery power and may even becheaper.

Conclusions:

MEMS technology has the potential to change our daily lives as much as the computer has. Si the material is used in the of the MEMS field at the preliminary stage. A thorough understanding of the properties of existing MEMS materials is just as important as the development of new MEMS materials.

Future MEMS applications will be uedsateelitecomunicationsby processes enabling greater functionality through higher levels of electronic-mechanical integration and greater numbers of mechanical components working alone or together to enable a complex action based on satellite and also automobilrapplications. Future MEMS products will demand higher levels of electrical and mechanical integration and more intimate interaction with the physical world. The high up-front investment costs for large-volume commercialization of MEMS will likely limit the initial involvement to larger companies in the IC industry. Advancing from their success as sensors, MEMS products will be embedded in larger non-MEMS systems, such as printers, automobiles, and biomedical diagnostic equipment, and will enable new and improved systems.

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