PROCESSING: MICRO MACHINING TECHNOLOGY

LITHOGRAPHY

Lithography in MEMS context is typically the transfer of a pattern into a photosensitive material by selective exposure to a radiation source such as light. A photosensitive material is a material that experiences a change in its physical properties when exposed to a radiation source. If a photosensitive material is selectively exposed to radiation (e.g. by masking some of the radiation) the pattern of the radiation on the material is transferred to the material exposed, as the properties of the exposed and unexposed regions differ.

This exposed region can then be removed or treated providing a mask for the underlying substrate. Photolithography is typically used with metal or other thin film deposition, wet and dry etching.

Electron beam lithography

Electron beam lithography (often abbreviated as e-beam lithography) is the practice of scanning a beam of electrons in a patterned fashion across a surface covered with a film (called the resist) ("exposing" the resist) and of selectively removing either exposed or non-exposed regions of the resist ("developing"). The purpose, is to create very small structures in the resist that can subsequently be transferred to the substrate material, often by etching. It was developed for manufacturing integrated circuits, and is also used for creating nanotechnology architectures.

The primary advantage of electron beam lithography is that it is one of the ways to beat the diffraction limit of light and make features in the nanometer region. This form of maskless lithography has found wide usage in photomask-making used in photolithography, low-volume production of semiconductor components, and research & development.

The key limitation of electron beam lithography is throughput, i.e., the very long time it takes to expose an entire silicon wafer or glass substrate. A long exposure time leaves the user vulnerable to beam drift or instability which may occur during the exposure. Also, the turn-around time for reworking or re-design is lengthened unnecessarily if the pattern is not being changed the second time.

Ion beam lithography

It is known that focused-ion-beam lithography has the capability of writing extremely fine lines (less than 50 nm line and space has been achieved) without proximity effect. However, because the writing field in ion-beam lithography is quite small, large area patterns must be created by stitching together the small fields.

Ion track technology

Ion track technology is a deep cutting tool with a resolution limit around 8 nm applicable to radiation resistant minerals, glasses and polymers. It is capable to generate holes in thin films without any development process. Structural depth can be defined either by ion range or by material thickness. Aspect ratios up to several 10^4 can be reached. The technique can shape and texture materials at a defined inclination angle. Random pattern, single-ion track structures and aimed pattern consisting of individual single tracks can be generated.

X-ray lithography

X-ray lithography, is a process used in electronic industry to selectively remove parts of a thin film. It uses X-rays to transfer a geometric pattern from a mask to a light-sensitive chemical photoresist, or simply "resist," on the substrate. A series of chemical treatments then engraves the produced pattern into the material underneath the photoresist.

Diamond patterning

A simple way to carve or create patterns on the surface of nanodiamonds without damaging them could lead to a new photonic devices.

Diamond patterning is a method of forming diamond MEMS. It is achieved by the lithographic application of diamond films to a substrate such as silicon. The patterns can be formed by selective deposition through a silicon dioxide mask, or by deposition followed by micromachining or focused ion beam milling.

ETCHING:

Etching processes

There are two basic categories of etching processes: wet etching and dry etching. In the former, the material is dissolved when immersed in a chemical solution. In the latter, the material is sputtered or dissolved using reactive ions or a vapor phase etchant.

Wet etching

Wet chemical etching consists in selective removal of material by dipping a substrate into a solution that dissolves it. The chemical nature of this etching process provides a good selectivity, which means the etching rate of the target material is considerably higher than the mask material if selected carefully.

Isotropic etching

Etching progresses at the same speed in all directions. Long and narrow holes in a mask will produce v-shaped grooves in the silicon. The surface of these grooves can be atomically smooth if the etch is carried out correctly, with dimensions and angles being extremely accurate.

Anisotropic etching

Some single crystal materials, such as silicon, will have different etching rates depending on the crystallographic orientation of the substrate. This is known as anisotropic etching and one of the most common examples is the etching of silicon in KOH (potassium hydroxide), where Si <111> planes etch approximately 100 times slower than other planes (crystallographic orientations). Therefore, etching a rectangular hole in a (100)-Si wafer results in a pyramid shaped etch pit with 54.7° walls, instead of a hole with curved sidewalls as with isotropic etching.

HF etching

Hydrofluoric acid is commonly used as an aqueous etchant for silicon dioxide (SiO 2, also known as BOX for SOI), usually in 49% concentrated form, 5:1, 10:1 or 20:1 BOE (buffered oxide etchant) or BHF (Buffered HF). They were first used in medieval times for glass etching. It was used in IC fabrication for patterning the gate oxide until the process step was replaced by RIE.

Hydrofluoric acid is considered one of the more dangerous acids in the cleanroom. It penetrates the skin upon contact and it diffuses straight to the bone. Therefore, the damage is not felt until it is too late.

Electrochemical etching

Electrochemical etching (ECE) for dopant-selective removal of silicon is a common method to automate and to selectively control etching. An active p-n diode junction is required, and either type of dopant can be the etch-resistant ("etch-stop") material. Boron is the most common etch-stop dopant. In combination with wet anisotropic etching as described above, ECE has been used successfully for controlling silicon diaphragm thickness in commercial piezoresistive silicon pressure sensors. Selectively doped regions can be created either by implantation, diffusion, or epitaxial deposition of silicon.

Dry etching

Vapor etching

Xenon difluoride - Xenondifluoride (XeF) is a dry vapor phase isotropic etch for silicon originally applied for MEMS in 1995 at University of California, Los Angeles.Primarily used for releasing metal and dielectric structures by undercutting silicon, XeF has the advantage of a stiction-free release unlike wet etchants. Its etch selectivity to silicon is very high, allowing it to work with photoresist, SiO , silicon nitride, and various metals for masking. Its reaction to silicon is "plasmaless", is purely chemical and spontaneous and is often operated in pulsed mode. Models of the etching action are available, and university laboratories and various commercial tools offer solutions using this approach.

Plasma etching

Modern VLSI processes avoid wet etching, and use plasma etching instead. Plasma etchers can operate in several modes by adjusting the parameters of the plasma. Ordinary plasma etching operates between 0.1 and 5 Torr. (This unit of pressure, commonly used in vacuum engineering, equals approximately 133.3 pascals.) The plasma produces energetic free radicals, neutrally charged, that react at the surface of the wafer. Since neutral particles attack the wafer from all angles, this process is isotropic.

Plasma etching can be isotropic, i.e., exhibiting a lateral undercut rate on a patterned surface approximately the same as its downward etch rate, or can be anisotropic, i.e., exhibiting a smaller lateral undercut rate than its downward etch rate. Such anisotropy is maximized in deep reactive ion etching. The use of the term anisotropy for plasma etching should not be conflated with the use of the same term when referring to orientation-dependent etching.

The source gas for the plasma usually contains small molecules rich in chlorine or fluorine. For instance, carbon tetrachloride ($CCl4$) etches silicon and aluminium, and trifluoromethane etches silicon dioxide and silicon nitride. A plasma containing oxygen is used to oxidize ("ash") photoresist and facilitate its removal.

Ion milling, or sputter etching, uses lower pressures, often as low as $10-4$ Torr (10 mPa). It bombards the wafer with energetic ions of noble gases, often $Ar+$, which knock atoms from the substrate by transferring momentum. Because the etching is performed by ions, which approach the wafer approximately from one direction, this process is highly anisotropic. On the other hand, it tends to display poor selectivity. Reactive-ion etching (RIE) operates under conditions intermediate between sputter and plasma etching (between 10–3 and $10-1$ Torr). Deep reactive-ion etching (DRIE) modifies the RIE technique to produce deep, narrow features.

Sputtering

Reactive ion etching (RIE)

In reactive-ion etching (RIE), the substrate is placed inside a reactor, and several gases are introduced. Plasma is struck in the gas mixture using an RF power source, which breaks the gas molecules into ions. The ions accelerate towards, and react with, the surface of the material being etched, forming another gaseous material. This is known as the chemical part of reactive ion etching. There is also a physical part, which is similar to the sputtering deposition process. If the ions have high enough energy, they can knock atoms out of the material to be etched without a chemical reaction. It is a very complex task to develop dry etches processes that balance chemical and physical etching, since there are many parameters to adjust. By changing the balance it is possible to influence the anisotropy of the etching, since the chemical part is isotropic and the physical part highly anisotropic the combination can form sidewalls that have shapes from rounded to vertical.

Deep RIE (DRIE) is a special subclass of RIE that is growing in popularity. In this process, etch depths of hundreds of micrometres are achieved with almost vertical sidewalls. The primary technology is based on the so-called "Bosch process" named after the German company Robert Bosch, which filed the original patent, where two different gas compositions alternate in the reactor. Currently there are two variations of the DRIE. The first variation consists of three distinct steps (the original Bosch process) while the second variation only consists of two steps. In the first variation, the etch cycle is as follows:

(i) SF6 isotropic etch;

(ii) C4F8 passivation;

(iii) SF6 anisoptropic etch for floor cleaning.
In the 2nd variation, steps (i) and (iii) are combined.

Both variations operate similarly. The C4F8 creates a polymer on the surface of the substrate, and the second gas composition (SF6 and O2) etches the substrate. The polymer is immediately sputtered away by the physical part of the etching, but only on the horizontal surfaces and not the sidewalls. Since the polymer only dissolves very slowly in the chemical part of the etching, it builds up on the sidewalls and protects them from etching. As a result, etching aspect ratios of 50 to 1 can be achieved. The process can easily be used to etch completely through a silicon substrate, and etch rates are 3–6 times higher than wet etching.

ION IMPLANTAION

An ion-implantation material-modification technique was applied to a micro-electro mechanical systems (MEMS) fabrication technique in order to enhance the functionality of MEMS. Ion implantation, which is well known as doping technology in semiconductor and surface modification technology, can alter the characteristics of a substrate by the addition of ions. However, when the object is a microscale device such as MEMS, such implantation involves metallurgy of the micro material, because size, depth, and area of the modified area are on the same order as the size of the microscale device. When the characteristics that can be controlled by ion implantation are combined with other properties, such mechanical, electrical, optical, and chemical, a wide range of characteristics can be easily controlled simply by changing the operating parameters, such as ion species, energy, dose, and substrate temperature. By effectively utilizing region selectivity, which is an advantage of ion implantation, the local physical properties of a micro device can be controlled. Consequently, in the design of MEMS devices, material properties can be controlled to enhance the functionality of the device. In this study, we used this ion implantation technique, which only involved injection of ions and etching that changed the chemical property of the substrate material, to fabricate a micro device, e.g., a microcantilever beam, that has low elasticity and electric conductance.

WAFER BONDING

Wafer bonding is a packaging technology on wafer-level for the fabrication of microelectromechanical systems (MEMS), nanoelectromechanical systems (NEMS), microelectronics and optoelectronics, ensuring a mechanically stable and hermetically sealed encapsulation. The wafers' diameter range from 100 mm to 200 mm (4 inch to 8 inch) for MEMS/NEMS and up to 300 mm (12 inch) for the production of microelectronic devices

In microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS), the package protects the sensitive internal structures from environmental influences such as temperature, moisture, high pressure and oxidizing species. The long-term stability and reliability of the functional elements depend on the encapsulation process, as does the overall device cost. The package has to fulfill the following requirements:

- protection against environmental influences
- heat dissipation
- integration of elements with different technologies
- compatibility with the surrounding periphery
- maintenance of energy and information flow

TECHNIQUES:

The commonly used and developed bonding methods are as follows:

- Direct bonding
- Plasma activated bonding

- Anodic bonding
- Eutectic bonding
- Glass frit bonding
- Adhesive bonding
- Thermo compression bonding
- Reactive bonding
- Transient liquid phase diffusion bonding

REQUIREMENTS:

The bonding of wafers requires specific environmental conditions which can generally be defined as follows:

1. substrate surface
    - flatness
    - smoothness
    - cleanliness
2. bonding environment
    - bond temperature
    - ambient pressure
    - applied force
3. materials
    - substrate materials
    - intermediate layer materials

The actual bond is an interaction of all those conditions and requirements. Hence, the applied technology needs to be chosen in respect to the present substrate and defined specification like max. bearable temperature, mechanical pressure or desired gaseous atmosphere.

EVALUATION:

The bonded wafers are characterized in order to evaluate a technology's yield, bonding strength and level of hermeticity either for fabricated devices or for the purpose of process development. Therefore, several different approaches for the bond characterization have emerged. On the one hand non-destructive optical methods to find cracks or interfacial voids are used beside destructive techniques for the bond strength evaluation, like tensile or shear testing. On the other hand the unique properties of carefully chosen gases or the pressure depending vibration behavior of micro resonators are exploited for hermeticity testing.

INTEGRATED PROCESSING

With the integrated process option the wafers are removed from the standard line and after the addition of micromachining steps return to the standard line. The position of the additional process steps is extremely important. In some cases the additional depositions are added after the main thermal processing but before the aluminium. Depending on the sensitivity of the electronics devices to thermal budget, a maximum thermal budget for the micromachining is determined.