ISSN: 2395-1680 (ONLINE)
DOI: 10.21917/ijme.2017.066

CONTAMINATIONS IN MEMS PROCESSES AND REMOVAL METHODOLOGY

Kamaljeet Singh
Systems Engineering Group, ISRO Satellite Centre, India

Abstract

Wafer impurities and process particulates are one of the prime reason of MEMS device failure. Various cleaning methodologies are evolved but cleaning remains a critical process in MEMS domain as varied materials along with micromachining operations are involved. Bulk and surface micromachining process results in etching of substrate as well as various layers which necessitate evolving of proper cleaning methodology to avoid device failure. This article details the sources of contamination, role of contamination in MEMS domain, cleaning and measurement techniques to mitigate the effect on the device performance.

Keywords:

MEMS, Contamination, Residues, Particulates, Defects

1. INTRODUCTION

The basic understanding of contamination directly results in improved reliability in semiconductor industry. The process requirements in semiconductor industries are varied compared to the standard processes associated with commercial industries. Photographic is the key process in the semiconductor industry but light is considered contaminant for this process [1]. So surface contaminants in semiconductor wafers can be categorized as:

- Thin film or molecular contamination (organic or inorganic)
- Anionic and Cationic contamination (ionic)
- Various impurities such as metals, chemicals, gases, de-ionized water, tool decomposition

Contaminations are one of the major concern for device yield in IC technology as the shrinkage of device geometry necessitate removal of impurities and the same concern is applicable for MEMS.As MEMS is the combination of both electrical and mechanical domain so impurities can effect either or both on the device performances [2]. MEMS devices are primarily passive devices but present trend of CMOS-MEMS integration demands the same level of cleaning methodology as prevalent in IC industry [3]. Surface roughness, residual stresses, thin membrane, and mechanical movement also plays an important role in MEMS which is different from CMOS. Process modules required to process mechanical devices, such as wafer deep etching of wafers, double-sided wafer alignment, and multiple wafer bonding which are unique in MEMS compared to IC industry [4]. Several steps must be evolved to understand internal variables and external variables to find out the root cause of contamination. Compared to IC industry, stiction and particle contamination are the major causes of MEMS device failure and defects like gases and water vapour give rise to additional stresses [5].

MEMS processes in general results in contaminants such as sodium ions, metals, substrate particles on the surface and can result in high failure rate. High temperature processing such as LPCVD, diffusion, annealing can diffuse or embed these impurities into various layers. Photoresist particles in particular can be detrimental in device performance and can leads to shorting conditions. The main effect of impurities is poor adhesion of deposited layers leading to delamination whereas ionic contamination leads to electrical defects, performance degradation, substrate leakage, resistivity variation, dielectric charging etc. Various bonding mechanisms such as anodic, eutectic, fusion needs proper cleaning methodology which is directly linked to device yield [6].

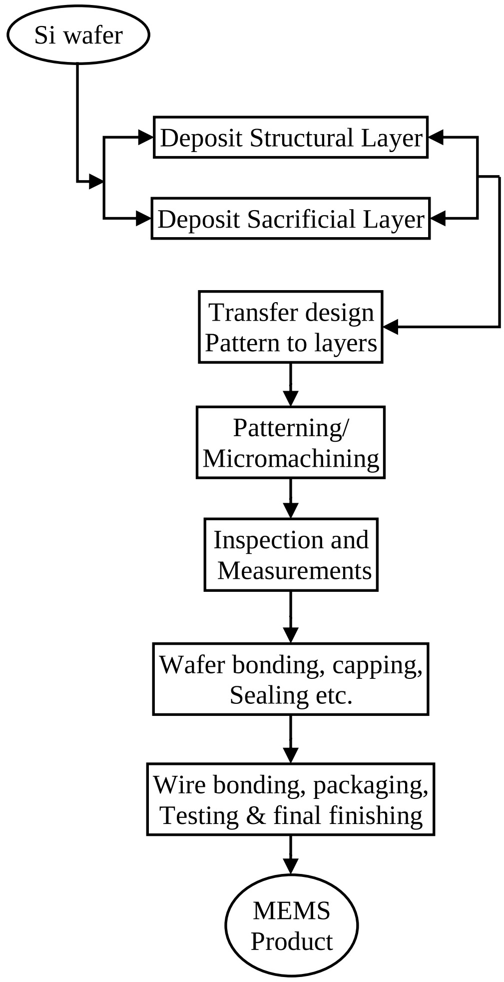


Fig.1. MEMS Process flow [5]

The ultimate potential of MEMS technology is to merge various miniaturized sensors, actuators, and structures onto a common silicon substrate along with integrated circuit [6]. The electronics are fabricated using standard CMOS process sequences whereas the micromechanical components are fabricated using compatible micromachining processes to form the mechanical and electromechanical devices. MEMS can be merged with microelectronics as well as with other technologies such as photonics thus paving way for heterogeneous integration. Due to material diversity the failure associated with MEMS device needs thorough understanding of various failure modes.

Out of many failure modes the most generic associated and least explored are the contaminations which can also cause latent defects resulting in poor reliability of the device. This article details the sources of contamination, prevalent cleaning methodologies, various failures associated with impurities and correlating the same with the measurement techniques.

2. MEMS PROCESS FLOW

The basic MEMS flow consists of mainly deposition, implantation, photolithography, etching and micromachining. The Fig.1 shows the basic fabrication steps in the realization of MEMS product.

As the critical dimensions of the pattern in MEMS is higher compared to IC, so failures related with scaling effect are not present. The Table.1 shows the basic process steps in CMOS and subsequent realization in MEMS domain [7]. MEMS processes are derived from CMOS and Table.1 shows analogy between them.

Table.1. CMOS process and subsequent layer in MEMS domain

CMOS Process	**MEMS Layer**
Implantation	Piezo-resistor, Electrode
Deposition/Oxidation	Structural, Sacrificial, Masking
Polysilicon	Resistor, Electrode, Structural
Metallization	Electrode, Membrane, Conductive Layer
Passivation	Structural Layer, Stress Compensation
…..	Micromachining
Thin wafer bonding	Bonding (Fusion, Eutectic, Anodic)

Sensor parameters such as offset, hysteresis, accuracy, repeatability are having greater impact due to contamination.

3. CONTAMINATION: TYPES AND SOURCES

The main contaminants on the silicon surfaces are: particles, metals, native oxide, metallic, organic and inorganic contaminants [7] The sources of contamination can be foreign materials or parasitic reactions and are within bulk of silicon wafer or due to surface phenomena. It can be due to chemicals, gases, tools, corrosion, handling, abrasion and parasitic reaction in between materials or dissolution of tool parts. It can be classified as:

- Contamination due to wafer contact such as various process, etchants, chemicals, gases, de-ionized water
- Contamination due to wafer handling and transportation
- Contamination due to overall facilities, human interventions and clean room environment

The sources of contaminations are shown in the Fig.2 which affects the reliability of the MEMS device. Contaminations are basically categorized as: ionic contamination, airborne molecular contamination and defect density. Ionic contamination comprises cations and anions that are physically adsorbed or chemisorbed. Organics particles sources are wet processes, lithography, dry etch polymers, chemicals and gases whereas inorganic sources are material outgassing, resist strips etc. Defect density occurs during the time of silicon crystal growth or due to process environment. MEMS processes are different from IC process basically in terms of micromachining process. The Table.2 shows the various materials employed in these processes.

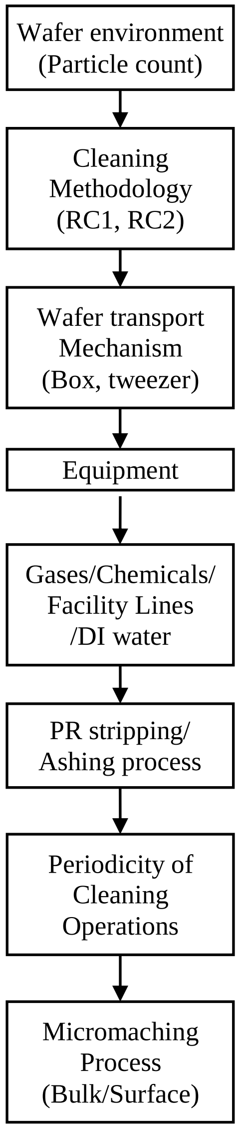


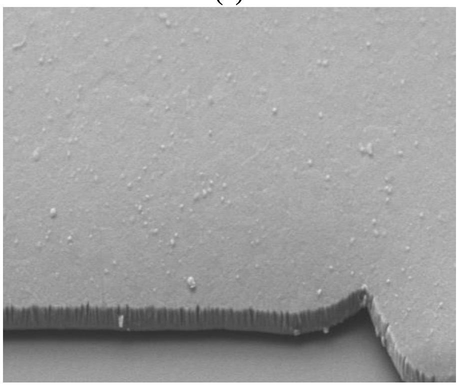
Fig.2. Flowchart showing various sources of contamination

Impurities on bare silicon surfaces can be due to contaminated films, discrete particles or adsorbed gases. Polymer (photoresist), solvent residues etc. are molecular compounds which can mask effective cleaning or rinsing. The main concern in the MEMS domain is the change of surface characteristics of the film due to chemical treatment. Corrosion, outgassing, handling and dissolution of tool body can also be cause of impurities which can diffuse through subsequent hot processes or results in chemical bonding such as ionic, covalent, van der walls. The bulk gases such as general and high purity nitrogen, argon, helium which are frequently used in processing should have low moisture and oxygen content. Also de-ionized water (DI) consists of silica, boron, sodium, dissolved oxygen and particulates which affects the resistivity of the water and can be cause of impurities.

Table.2. Overview of generic materials employed in micromachining process

Processes	Bulk micromachining	Surface micromachining
Diaphragm/Base layer deposition (furnace)	SiO/SiN	SiO & SiN
Active/Conductive layer (Deposition& patterning)	Poly-Si,Ti,Al	Doped poly, Al
Passivation/Sacx. layer (Deposition & patterning)	SiO &/SiN	PECVD SiO, Polyimide or PSG/BPSG
Metal/Structural layer (Deposition & patterning)	Al/Au/Poly	Al, Au, SiN, Poly
Chemistry	Wet (KOH,TMAH) DRIE	HF, HF+Glycol, CPD, vapor HF

(a)



(b)

Fig.3. Impurities on the processed devices (a) bulk micromachined (b) membrane of surface micromachined

The Fig.3 shows that after micromachining process, cleaning is needed to remove the particulates but standard rinsing and drying technique may lead to failure due to fragile membranes. Further particulates due to dicing and assembly also contaminate the structure which cannot be removed with standard techniques of hot forced air drying. So either carrying out surface micro-machining process after dicing or wafer level capping techniques is to be adopted, alternatively vapour phase cleaning to be carried out to remove the particulates.

Failure mechanism commonly encountered in MEMS domain are-stiction, mechanical fracture, cracks, wear, delamination, stresses, humidity, radiation, temperature, ESD and contamination [8]. Contamination related failures is least explored in all the failures which is responsible for malfunctioning and unpredictable behaviour. Also electrical shorts and open can be caused due to stiction which can be due to impurities or particulates. Certain fabrication steps can results in particulates that can be latent and can cause failure at later stages. The foundry processes are optimized to mitigate these failures by framing clean room protocols.

4. CLEANING METHODOLOGY AND MITIGATION TECHNIQUES

Cleaning control the contamination and in some cases avoid contamination which can penetrate or diffuse in various layers. Standard brush using IPA (isopropyl) is employed for PCB cleaning but on silicon wafer it can cause surface roughness and more particulates. The main cleaning agents are detailed in the Table.3.

Table.3. Cleaning agent employed in MEMS

Cleaning Agent	Composition	Remarks
SC-1	$NH_4OH+H_2O_2$	Organics
SC-2	$HCl+H_2O_2$	Organics & Inorganics
FSI	$NH_4OH+H_2O_2+HCl$	Organics & Inorganics
Piranaha	$H_2SO_4+H_2O_2$ (1100°C)	Photoresist
HF	Buffered (NH_4F+HF), Diluted & Standard HF	Dielectric/Native oxide
EKC	EKC+IPA (650°C)	Polymer
Ultrasonic	DI Bath	Removing surface impurities
Megasonic	DI Bath (megasonic frequency with varied power)	Removing surface impurities
Rinsing & Drying	DI water	To remove particulates observed in process
Plasma operation	Ar gas	Etching and ashing

The surface properties alter from hydrophobic to hydrophilic with interaction of certain chemicals which are detrimental in surface micromachining process. Boron in BPSG layer which is employed as sacrificial layer can easily diffuse into various layers and can change the characteristics such as stress, melting point, etch rate etc. Also keeping into consideration that impure H_2O_2 results in Al on silicon wafer and stirring in pyrex glass instead of quartz results in ionic impurities, proper care to be taken in carrying out the requisite processes.

4.1 MITIGATION TECHNIQUES

Defects or impurities can generate nucleation sites and can further diffuse into various layers with subsequent processes. This may change the stress or can hamper effective etching or bonding operations. Signature of failure mode reflects defect but it needs measurement techniques along with analytical skill to correlate the failure and find out the cause. Impurities cause unpredictable behaviour which is difficult to predict. This demands strict process control with all cleaning protocols to be adhered. The approach of controlling the process with various dummy runs as shown in Fig.4 before carrying out production run is an effective means to find out the root cause.

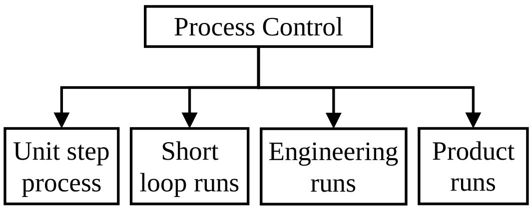


Fig.4. Process control steps

RF pre clean and plasma clean (13.5MHz) are also employed to avoid impurities on the wafer surface. Another consideration to be encountered in MEMS devices is the alteration of surface energies from hydrophobic to hydrophilic due to glow discharge alters. Also the vessels for keeping chemicals, gases lines, storage place, clear room air also contributes in controlling impurities along with purity of chemicals and gases to be ensured. ULPA filters, temperature, humidity control, differential pressure, vibration free platform are the other mechanism to maintain the clean room environment. The Table.4 shows the identifying technique correlating with the particle sizes.

Table.4. Particle size and measurement technique

Particle nomenclature	Sizes (nm)	Technique
Macro	>50,000	Naked eye
Micro	100-50000	Optical Microscopy
Submicro	10-100	Optical Microscopy
Nano	1-100	Electron and probe microscopes
Atomic	0.01-1	Holography
Subatomic	<0.01	Spectroscopy

The non-removal of impurities can lead to pin holes, cracks, material voids and various dislocations of the deposited films. Both in-line and off-line technique can be employed to detect metallic contamination, anions impurities, chemical composition which can be measured using ion chromatograph, gas chromatograph, EDX techniques [9]. Total organic compound analyzer is detected for DI water whereas sheet resistivity and particle counter along with CPX tool are being used for resistivity and wafer surface characterization.

5. CONCLUSION

The emerging MEMS sensing applications are in the area of infrared, fluidics, chemical and biological domain. MEMS devices are having bigger feature size and are passive in nature so the effect of contamination is not detrimental as compared to IC having low geometry. But certain impurities such as moisture and their nature affects the repeatability and yield of the devices resulting in stress, resistivity variation and stiction. High temperature processing or high electric field in MEMS devices can lead to impurities to diffuse or surface phenomena such as chemical bonding leads to electrical defects and device failure. Bonding is also major process in some MEMS products and quality of bond is dependent on the surface condition. Critical aspects in MEMS domain is the fragility of the structures after micromachining so after certain steps generic air drying and rinsing is avoided. Contamination related failures due to micro-contaminants are the major cause of poor yield ultimately translating into higher cost. Repeatability and reproducibility of device is also affected by the impurities which can be easily plugged by employing effective cleaning methodology and techniques. This article presents an overview of the contaminants and various cleaning methodology along with mitigation techniques to reduce failure mechanism.

REFERENCES

[1] Rajiv Kohli and K.L. Mittal, "*Developments in Surface Contamination and Cleaning*", 1st Edition, Elsevier, 2014.

[2] Gary K Feeder, "MEMS Fabrication", *Proceedings of IEEE-ITC International Test Conference*, pp. 691-698, 2003.

[3] Mohamed Gad-el-Hak, "*The MEMS Handbook*", 2nd Edition, CRC Press, 2002.

[4] G.K. Ananthasuresh, K.J. Vinoy, S. Gopalakrishnan, K.N. Bhat and V.K. Aatre, "*Micro and Smart Systems*", Wiley, 2010.

[5] Janusz Bryzek, "*Principles of MEMS: Handbook of Measuring System Design*", John Wiley and Sons, 2011.

[6] Werner Kern, "The Evolution of Silicon Wafer Cleaning Technology", *Journal of Electrochemical Society*, Vol. 37, No. 6, pp. 1887-1892, 1990.

[7] Chandan Kumar Sarkar and Sunipa Roy, "*MEMS and Nanotechnology for Gas Sensors*", CRC Press, 2015.

[8] Kamaljeet Singh and A.V. Nirmal, "Reliability Aspects in RF-MEMS Circuits for Space Applications", *Journal of Engineering and Technology Research*, Vol. 4, No. 6, pp. 1-11, 2016.

[9] J. Grym, "*Semiconductor Technologies*", InTech Publisher, 2010.