FABRICATION OF COST EFFECTIVE MICROBOLOMETER USING FRONT END BULK MICROMACHINING

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The Degree of Master of Technology

Under the Guidance of
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Dedicated to

My Family and Friends…..

Abstract

Frontend bulk micro machining is one of the proven techniques of making suspended microstructures and is highly adapted due to its simple and cost effective way of fabricating the devices. In this thesis we propose a low-cost un-cooled infrared micro-bolometer detector, where the Si itself is used as the infrared sensitive material. The process does not required any diffusion or electrochemical etch-stop technique as is required in traditional CMOS line micro-bolometer fabrication. Rather we are reporting two ways of fabricating the device. The first method is done by frontend bulk micromachining using wet etching which helps us realize the device with relatively low cost as compared to other proposed method of fabricating the device. The second uses both dry and wet etching which reduces the area per pixel. In this work we adapt the geometric mask design such that the openings are aligned at 45° to wafer prime flat of silicon (100) wafer and act as etch openings for frontend bulk micromachining. The fabrication process was simulated using Intellisuite FABSIM based physical simulator. The proposed concept was experimented and verified by fabricating micro bridges/ cantilevers. Further the same concept was applied to fabricate micro-bolometer (IR sensor).

Contents

Chapter 1

Introduction

Infrared radiation is part of the electromagnetic spectrum with wavelengths above visible spectrum ranging from 1 µm to several tens of µm. Detectors that can sense the infrared radiation are called infrared detectors, and ensembles of the infrared detectors in (one or) two dimensional arrays are called focal plane arrays (FPAs). Infrared detectors are used in many military and commercial applications such as night vision, mine detection, reconnaissance, firefighting, medical imaging, and industrial control.

There are basically two types of infrared detectors used in the FPAs for infrared imaging applications: photon and thermal detectors. In photon detectors, the absorbed infrared photons generate free electron-and-hole (E-H) pairs, which are collected by an applied electric field for electronic processing. For proper operation, the photon detectors need to be cooled down to cryogenic temperatures, such as 77 K or lower, hence they are also called cooled infrared detectors. There are very high performance photon detector FPAs in the market, however their costs are very high for many commercial and even for some military applications. In order to achieve lower cost infrared FPAs, a different technology has been developed known as the thermal infrared detector technology. In thermal detectors, the energy of the absorbed infrared photon rises the temperature of the detector, and the change in one of the electrical parameter due to the temperature change is measured with the help 2 of proper electronic circuitry. Thermal detectors can operate at room temperature without the need for cryogenic coolers; therefore they are also called uncooled infrared detectors. Despite their lower directivity values, these detectors have recently gained wide attention due to their advantages such as low cost, small size, and low power.

1.1 Infrared Spectrum

Infrared radiation is part of the electromagnetic spectrum with wavelengths above visible spectrum ranging approximately from 1 µm to 1000 µm [1], which is called the infrared spectrum discovered first in 1800 by William Hershel, who discovered a type of invisible radiation in the spectrum beyond red light, by means of its effect upon a thermometer. Most of the thermal radiation emitted by objects near room temperature is infrared. Infrared radiation can be used to remotely determine the temperature of objects (if the emissivity is known), this is termed thermography. Figure 1.1 shows the complete electromagnetic spectrum of light with important spectral regions. Infrared spectrum is divided into sub-regions called short-wave infrared (SWIR: 1 µm - 3 µm), mid-wave infrared (MWIR: 3 µm - 6 µm), long-wave infrared (LWIR: 6 µm – 16 µm), and far infrared (FIR: > 16 µm) [1]

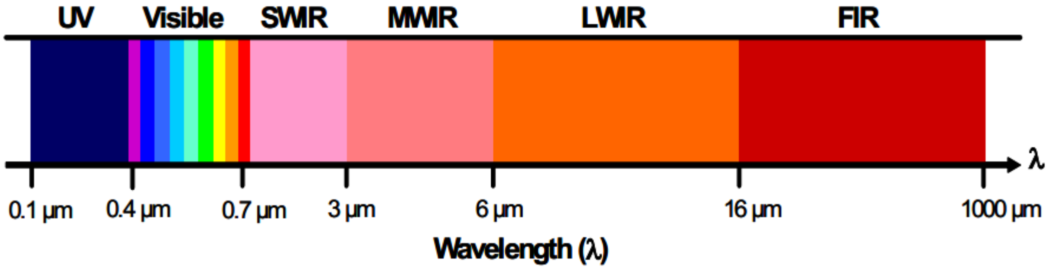


Fig.1.1: Electromagnetic spectrum of light with important spectral regions [1]

Thermographic cameras detect radiation in the infrared range of the electromagnetic spectrum (roughly 9,000–14,000 nanometers or 9–14 µm) and produce images of that radiation, called thermograms. Since infrared radiation is emitted by all objects above absolute zero according to the black body radiation law, thermography makes it possible to see one's environment with or without visible illumination. The amount of radiation emitted by an object increases with temperature; therefore, thermography allows one to see variations in temperature. When viewed through a thermal imaging camera, warm objects stand out well against cooler backgrounds; humans and other warm-blooded animals become easily visible against the environment, day or night. As a result, thermography is particularly useful to military and other users of surveillance cameras. Specialized thermal imaging cameras use focal plane arrays (FPAs) that respond to longer wavelengths (mid-and long-wavelength infrared). The most common types are InSb, InGaAs, HgCdTe and

QWIP FPA. The newest technologies use low-cost, uncooled microbolometers as FPA sensors. Their resolution is considerably lower than that of optical cameras, mostly 160x120 or 320x240 pixels, up to 640x512 for the most expensive models. Thermal imaging cameras are much more expensive than their visible-spectrum counterparts, and higher-end models are often export-restricted due to the military uses for this technology. Older bolometers or more sensitive models such as InSb require cryogenic cooling, usually by a miniature Stirling cycle refrigerator or liquid nitrogen.

1.2 Types of infrared detectors

There are basically two types of detectors that can sense the infrared radiation. The first type is the photon detectors, where the absorbed infrared photons generate free electron-and-hole (E-H) pairs, which are then collected by the application of electric field for electronic processing. The second type of infrared detectors are known as thermal detectors, where the energy of the absorbed infrared photon rises the temperature of the detector, and the temperature induced change in one of the electrical parameters is measured with the help of a proper electronic circuit.

Photon infrared detectors are fast, and their sensitivities are much higher as compared to thermal detectors. However, the number of thermally generated E-H pairs are much higher than the infrared induced E-H pairs at room temperature, which makes their use for infrared imaging impossible especially in the LWIR range unless they are cooled down to cryogenic temperatures such as 77 K or below. For this purpose, special and expensive coolers are used, increasing the size, cost, and operating power of the detector systems or cameras. Commonly used cooled detectors are fabricated using Indium Antimonide (InSb), Mercury Cadmium Telluride (HgCdTe or MCT), or Quantum Well Infrared Photodetector (QWIP) technologies. The fabrication of these detectors involve complicated processing steps due the known difficulties of handling low-bandgap materials required for the detection of low energy infrared photons. Therefore, the cost of the 6 photonic detectors and infrared cameras using photonic detectors are very high, finding application areas only in expensive weapon platforms, in astronomical observation instruments, or special medical instruments, where the performance is the primary issue. On the other hand, the infrared cameras using thermal detectors are small in size, consume less power, and are low-cost, making them ideal choice for applications which require high unit numbers with relatively lower performance.

1.3 **Thermal (Uncooled) Infrared detector**

Thermal or uncooled infrared detectors sense the change in an electrical parameter upon the change in the device temperature related with the amount of absorbed infrared energy. Therefore, thermal detection mechanism is an indirect way of infrared detection, and the response time of these detectors are longer as compared to the photon detectors. In most of the cases, signal-to-noise ratio and directivity of the uncooled thermal detectors are lower than that of the cooled photon detectors. Therefore, the performance of the thermal detectors is lower than the cooled photon detectors. Since the electrical bandwidth of the staring arrays is much lower than the scanned arrays, it is possible to improve the signal-to-noise ratio of the thermal detectors when operated in staring arrays. Furthermore, it is relatively easier to fabricate staring array using thermal detectors as compared to the arrays that use cooled photon detectors. Furthermore, at scanning speeds close to the TV frame rate (30 frames/sec), the performance degradation of the thermal detectors due to their relatively longer thermal time constants can be minimized by proper detector design. Considering these factors, although the cooled detector arrays still provide better performances, the performance difference between the thermal and cooled photonic detectors becomes smaller than what is expected by just comparing them on pixel basis [2]. The most important advantage of the thermal detectors is that they can operate at room temperature without requiring any complex and expensive cooling 7 equipment. The resulting infrared imaging systems utilizing the uncooled detector technology have much smaller size, lower cost, lower power consumption, and extended operation durations. Due to these advantages uncooled detectors are used in many military and commercial applications, such as night vision, mine detection, driver night vision enhancement, firefighting, and industrial control applications.

There are basically four types of thermal infrared detectors: 1) resistive microbolometers, 2) pyroelectric and ferroelectric detectors, 3) thermoelectric detectors, and 4) diode microbolometers. Although, there are some other thermal infrared detection mechanisms, such as heat-balancing and microcantilever thermal detectors, only the above four detector types have been widely used in the practical uncooled thermal imaging applications

1.4 Brief History of Bolometer and infrared detector

The IR radiation had been unknown until 200 years ago when Herschnel's experiment with thermometer was reported in April 1800. This thermometer was a crude monochromator which used thermometer as a detector so the energy distribution in sunlight could be measured. The Fig. 1.2 shows the milestones of IR detectors development. In 1829, Nobii constructed the first thermophile by connecting a number of thermocouples in series. In 1933, Melloni modified thermocouple design by using bismuth and antimony for it. Another step was the appearance ofLangley's bolometer in 1880. Two thin platinum foil ribbons were connected as two arms of Wheatstone bridge in the bolometer. Langley continued to develop his bolometers for following 20 years, and his later devices were 200 times more sensitive than his first devices.

The Langley's last bolometer was able to measure the heat from a cow at distance of a quarter of mile, so that is considered as the milestone in the development of IR detectors connected with thermal detectors. The thermoelectric effect was discovered by Seebeck in 1921, and soon thereafter he demonstrated the first thermocouple which was very important step in IR detection development [3]. In history, there have been investigated many materials in the IR field, and many physical phenomena have been proposed for IR detection. The important physical principles used in the development of IR detection are thermo-electric power (thermocouples), change in electrical conductivity (bolometer), gas expansion (Golay cell), pyroelectricity (pyro detectors), photon drag, Josephson effect (Josephson junction), internal emission (PtSi Schottky barriers), fundamental absorption (intrinsic photo-detectors), impurity absorption (extrinsic photodetectors), low-dimensional solids (super lattice and quantum well detectors), different type of phase transition, etc.

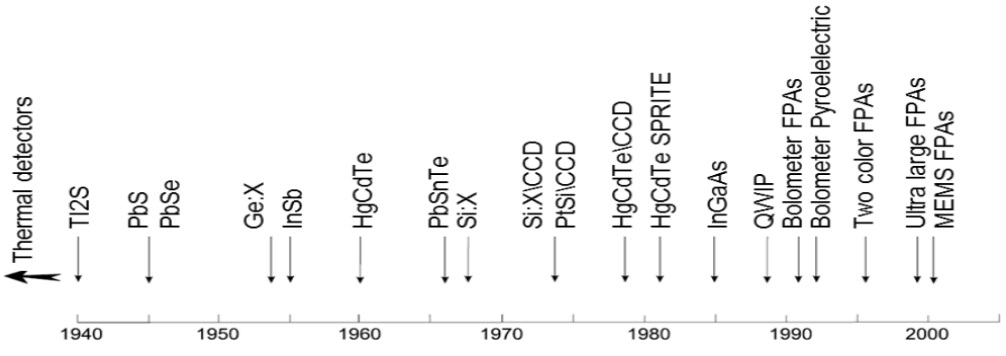


Fig.1.2: History of IR detectors development [3]

A microbolometer is a specific type of bolometer used as a detector in a thermalcamera.Infrared radiation of wavelength ranging between 7.5-14 um strikes the detector material heats it, and thus changes its electrical resistance. This resistance change is measured and processed into temperatures which can be used to create an image. Unlike other types of infrared detecting equipment, microbolometers do not require cooling.

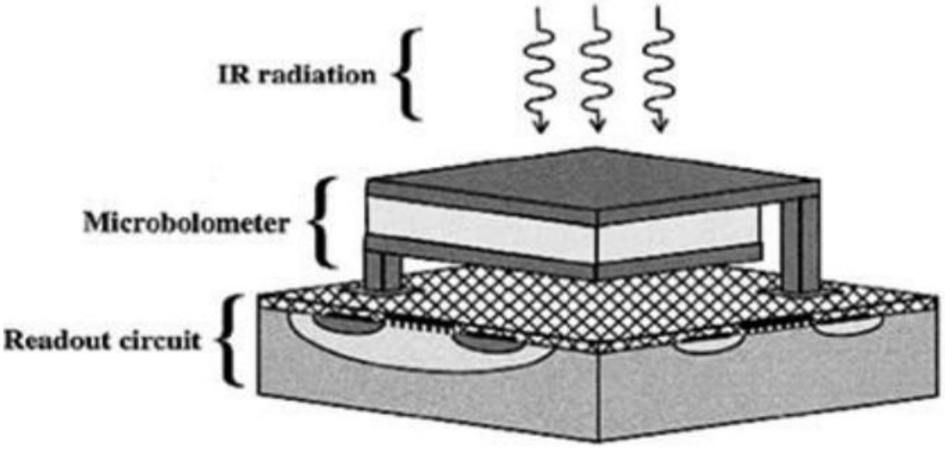


Fig.1.3: Microbolometer and Readout circuit [4]

1.5 Motivation

An infrared sensor is an electronic instrument that is used to sense certain characteristics of its surroundings by either emitting and/or detecting infrared radiation. It is also capable of measuring heat of an object and detecting motion. The IR sensor has verity of applications as mentioned below

- Tracking and art history.
- Climatology, meteorology, and astronomy.
- Thermography, communications, and alcohol testing.
- Heating, hyperspectral imaging, and night vision.
- Biological systems, photobiomodulation, and plant health.
- Gas detectors/gas leak detection.
- Water and steel analysis, flame detection.
- Anesthesiology testing and spectroscopy.
- Petroleum exploration and underground solution.
- Rail safety.

Below shown are some pictures taken by microbolometer sensors and their field of applications [13].

Fig.1.4: Night time Surveillance applications

Fig.1.5: Valuable tool for firefighters, can see through smoke

Fig.1.6: In Medical Monitoring

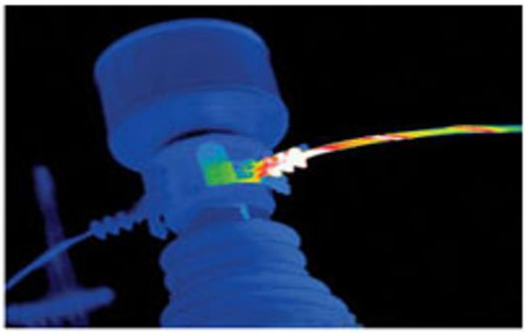


Fig.1.7: Identifying unexpected heat loss in electrical connections

Fig.1.8: Automotive Night Vision

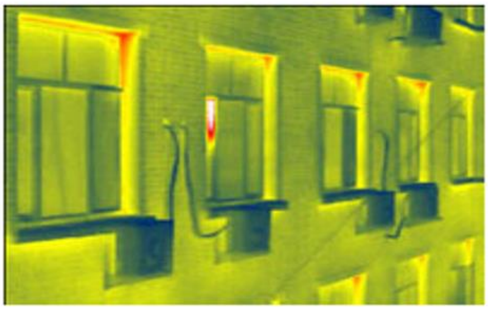


Fig.1.9: Energy Conservation (identify heat loss in homes and buildings)

As mentioned above the IR sensor/detector is used in many fields of applications. Hence the quality of image, sensitivity of the device and cost play very important role in different field of applications. For example in astronomy the sensitivity of the device matters more as it has to detect asteroids from distance places but in biomedical applications rather than sensitivity cost matters a lot.

1.6 Research Objectives and Thesis Organization

Main objective of the thesis was to make the commercial based IR sensor, microbolometer in ultra-low cost and simple method of fabrication. Our aim was initially to make the Microbolometer sensing element using simple process steps and then go for 3D integration of the sensor with its corresponding ROIC, so that the sensing membrane with its ROIC can be available as a complete package. This will be of low cost and efficient IR sensor with considerable reduced effort.

Before going for bolometer fabrication, a simple Si cantilever/microbridge structure was fabricated, which could be the basic structure for the microbolometer. We started with the traditional electrochemical wet etching process to fabricate the Si microbridges and end up with novel idea to fabricate Si microbridges, which was low cost method to fabricate microbridges. Then this technique is used and tried to fabricate the microbolometer structure which is also of low cost.

The Organization of the thesis and the contents of the following chapters can be summarized as follows:

1. Chapter II gives the brief literature survey of the Bolometer and its temperature sensing materials.
2. Chapter III introduces the concept of Surface bulk Micromachining and also presents the different fabrication techniques to make silicon microbridges.
3. Chapter IV presents the design and fabrication of efficient microbolometer structure and its fabrication process flow.
4. Chapter V gives the fabrication results of the microbolometer of dry and wet etching process.
5. Chapter VI concludes the thesis with future scope of work.

Chapter 2

Literature Survey

2.1 Fabrication of Si Microbridges and Cantilevers

Micro-electro-mechanical systems (MEMS) consist of mechanical components as well as electronic circuits integrated with each other as a complete system. Micro fabrication plays a very important role in miniaturizing the mechanical components as a result of which those devices are capable of integrated with electronics which as a whole system can be implemented in chip giving very good performance. Surface and bulk micromachining [5] are the two most important processes to make mechanical components. Being simple and cost effective way of removing parts of Silicon, anisotropic wet etching is highly demanded in MEMS processes to make different types of sensors and actuators.

Microcantilevers and microbridges are the frequently used structures in many of MEMS devices and simple structures are also used as thermal, mechanical and biomolecule detectors. So the ease and cost of process is highly dependent of the fabrication of those microstructures. There are majorly three methods to fabricate Si Microbridges/cantilevers.

i. By using a sacrificial layer.
ii. SOI method.
iii. Bulk micromachining.

Using a sacrificial layer for making the device causes the ease of fabrication difficult similarly using an SOI wafer makes the cost of the process high. But bulk micromachining of Si to make the microbridge/cantilever is one of the simple and cost effective ways to fabricate the microbridges/cantilevers.

2.2 Microbolometer and Fabrication

Bolometers are nothing but the Heat or IR sensors in which basically the resistance of the device get changed with the absorbed IR radiation. Every living and non-living objects have certain thermal signature, the device is able to detect the object from the IR radiation emitting from it. Hence it has a wide range of applications such as night vision, infrared imaging, biomedical applications such as skin cancer, early tooth cavity detection except these it also used in astronomy and so on. Microbolometers are getting more attention because of its light weight, low cost and low power usage. But the challenge lies in implementing very large format arrays at low cost.

A lot of techniques have been reported so far to fabricate microbolometers and array of it. The most commonly used manufacturing approach for uncooled infrared bolometer FPAs is monolithic integration [6], which is shown below.

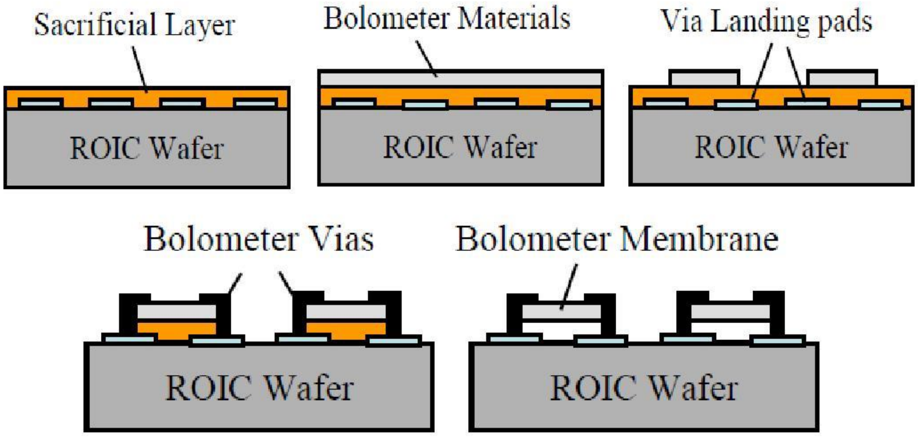


Fig2.1: showing monolithic method of bolometer fabrication [6]

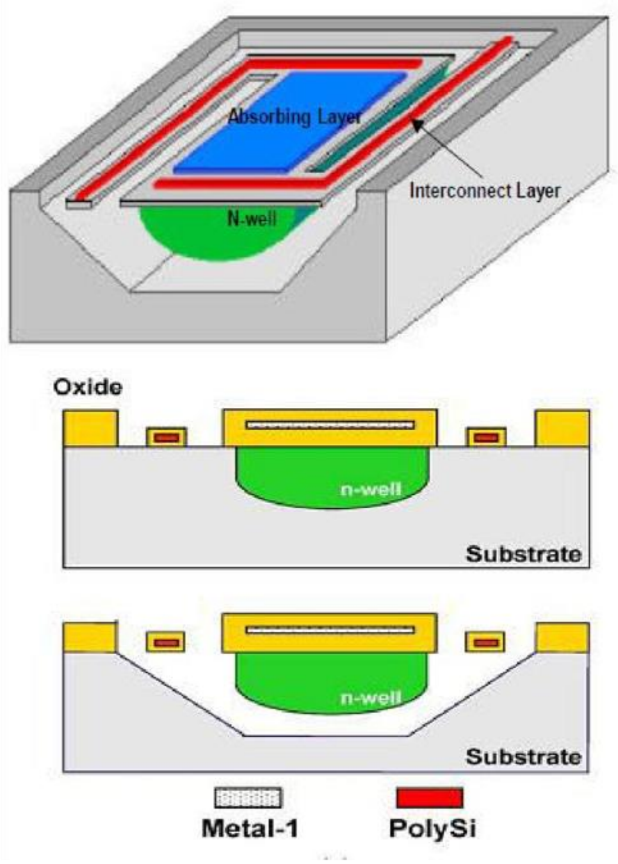
In this method ROIC is pre-manufactured then on top of that a high temperature polyamide is deposited as sacrificial layer. The bolometer material (ex. VOx) is deposited on top of that which is then patterned and bolometer vias are created for contact, then by using oxygen plasma the sacrificial layer is removed which results in free isolated bolometer.

But the disadvantages we observed in this method are

(1) Some monocrystaline bolometer materials require more than 450 degree centigrade for deposition which may damage our underlying ROIC at that temperature.

(2) As the structure obtained in this method is hanging without any support so the reliability is the major concern in this method.

The second method of fabrication is the bulk micromachining the fabrication is done in CMOS line after the ROIC is made shown in fig.2.2 [7] [8]. In this method of fabrication electrochemical etch stopping technique [9] is used for which there require n-well layers in p-type substrate and those n-wells are used as the sensing elements.fig.2.2 shows the bolometer device obtained using bulk micromachining.



- Fig.2.2: showing the front view of CMOS line microbolometer [6]

In this method the bolometer is fabricated in standard CMOS line i.e. first the ROIC is fabricated and after that bulk micromachining is done by electrochemical etching method where an n-well is used as the etch stop layer.

But the disadvantages got in this method are

(1) The ROIC cannot place beneath the bolometer membrane which reduces the pixel form factor.

(2) The end step is the electrochemical wet etching step which required potential to apply for the etching to be stopped in sensor membrane which is cumbersome while going for array of bolometers and may not be good for the ROIC.

Then the third important method to fabricate microbolometer is 3D integration [10], which avoids the high temperature issue in monolithic for which it was difficult to put some monocrystaline material on top of ROIC wafer. The process steps are shown in fig.2.3.

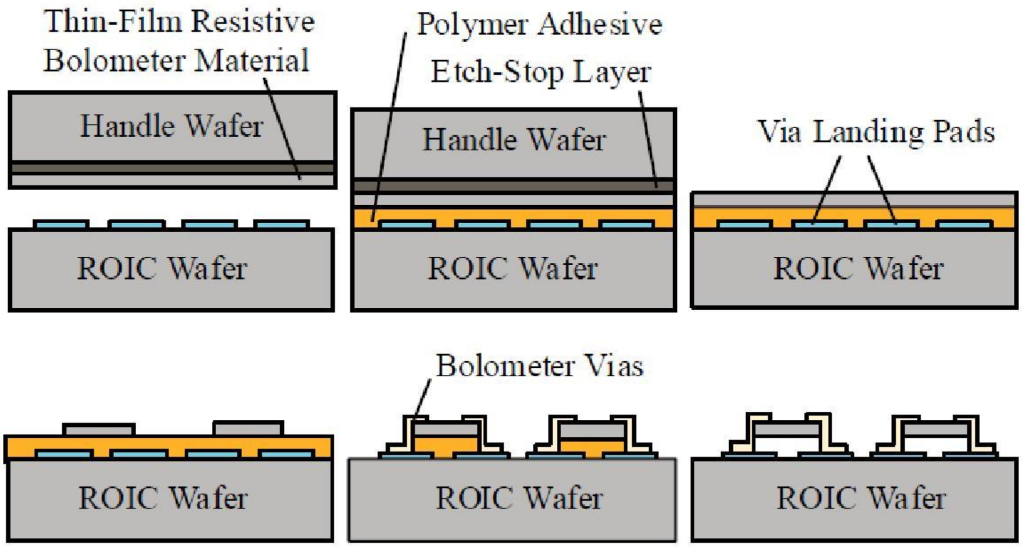


Fig.2.3 showing the heterogeneous 3D Integration of Bolometer

But the issues lying in the above method are

(1) The method suffers from reliability issue.

(2)The process is costly as it requires a handle wafer which is normally SOI.

2.3 Bolometer Temperature Sensing materials

The temperature sensing material is one the most important issues to obtain the high sensitive IR detector. The suitable material for such application has to have high temperature coefficient of resistance (TCR), and low 1/f noise value. Considering the common commercial applications, the sensing material has to be compatible for integration to read-out circuits. Today, the most used materials are vanadium oxide (VOx), amorphous silicon (α-Si), and silicon diodes. The vanadium oxide films used to have the TCR in the range of 2 %/K and 3 %/K at room temperature. Today, the bolometer characteristics using this layer can be improved by employing the vanadium-tungsten oxide made by low temperature oxidation of vanadium-tungsten metal films. Another effect on the layers has been achieved by using the reactive pulsed deposition for Ti-W layer, and today, it is possible to obtain a VOx layers with TCR of 5.12 %/K. The VOx film is the most used in present bolometer products [3, 11, and 12].

The amorphous silicon (α-Si) is also applied in numerous bolometer devices. The α-Si microbolometer arrays have advantage of complete compatibility to silicon fabrication technology, high optical absorption and TCR is up to about 3 %/K. The bolometer made of α-Si commonly consists of thin suspended membrane which leads to low thermal time constant, and low thermal conductivity. The α-Si based bolometer arrays are cheaper to fabricate for high volume application [3, 11, 12].

There have been many attempts to replace the resistive temperature sensors with semiconductor diode made of single-crystal for its stability and the low value of the noise. Diode has an advantage of multi modes running, it can operate as constant current or constant voltage even at the biased or reverse biased. The most challenging issue is the thermal isolation of this structure.

A simple alternative for temperature sensing material are thin film metals. They are easy to integrate with CMOS ROIC process and the 1/f noise is low. TCR is unfortunately also very low (e.g. Titanium up to 0.35 %/K), which results in low performance detectors. Titanium is preferred due to its low thermal conductance.

An alternative to α-Si are different types of amorphous germanium-silicon-oxygen compounds (GexSi1-xOy) grown by reactive sputtering in an Ar or Ar: O2 environment, or by plasma enhanced chemical vapor deposition. The Ge content is in the order of 85%. TCR values up to 5.1 %/K have been reported, but the relatively high 1/f noise lower the potential detector performance. The advantage is lower thermal conductance.

Chapter 3

Silicon Bulk Micromachining

3.1 Frontend Bulk Micromachining to make silicon Microbridges

Frontend bulk micro machining is one of the proven techniques of making suspended microstructures and is highly adapted due to its simple and cost effective way of fabricating the devices. Here we propose novel geometric mask designs for achieving area efficient microstructures by frontend Si bulk micromachining.

In this work a geometric mask design having a microstructure between two rectangular openings is adopted. These openings are aligned at 45º to wafer prime flat of (100) silicon wafer and act as etch openings for frontend bulk micromachining. Alignment of the mask patterns relative to wafer crystallographic orientation is critical in the fabrication of many MEMS devices.

Etch rate of anisotropic wet etchant varies depending on the crystal plane exposed. Etch rate is lower on more densely packed surface than that of loosely packed surface so etch rate of (100)> (110)> (111). The structure and dimension of the pattern etched on Si substrate depends not only on the orientation of Si substrate but also on geometry of opening, its alignment relative to wafer's crystal axes and the duration of etching [10]. Fig.3.1 shows the Si wet etch in (100) wafer where the mask is aligned in (110) direction. As shown the etched pattern obtained is bounded by four (111) planes and all those four planes make an angle of 54.7 degree with respect to the surface plane. But if we make the mask aligned in the (100) direction in (100) wafer then there can be seen significant undercut inside the mask layer. Si is not only etched in vertical direction but also etched in horizontal direction as all of the exposed planes are (100) in nature[14]. Fig.3.2 shows the etching in (100) wafer where mask oriented in (100) direction.

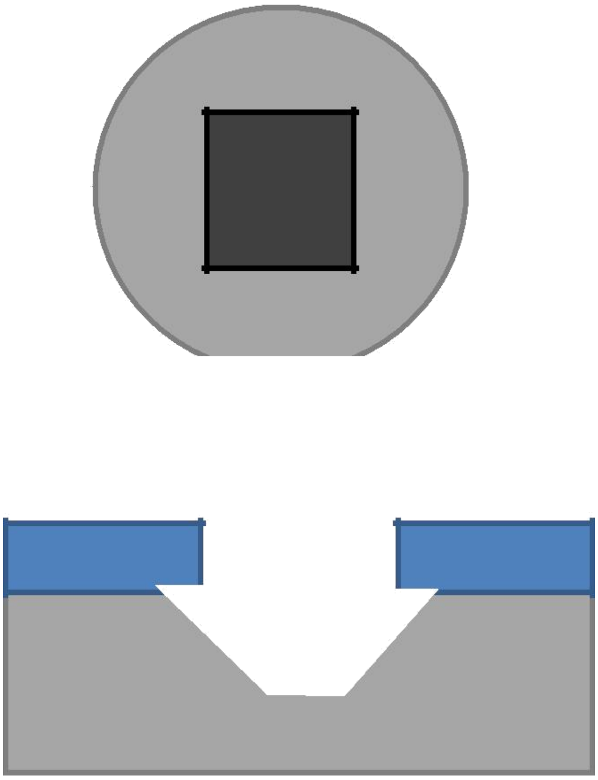


Fig.3.1: Showing etching in (100) plane with the shown mask orientation with respect to wafer flat

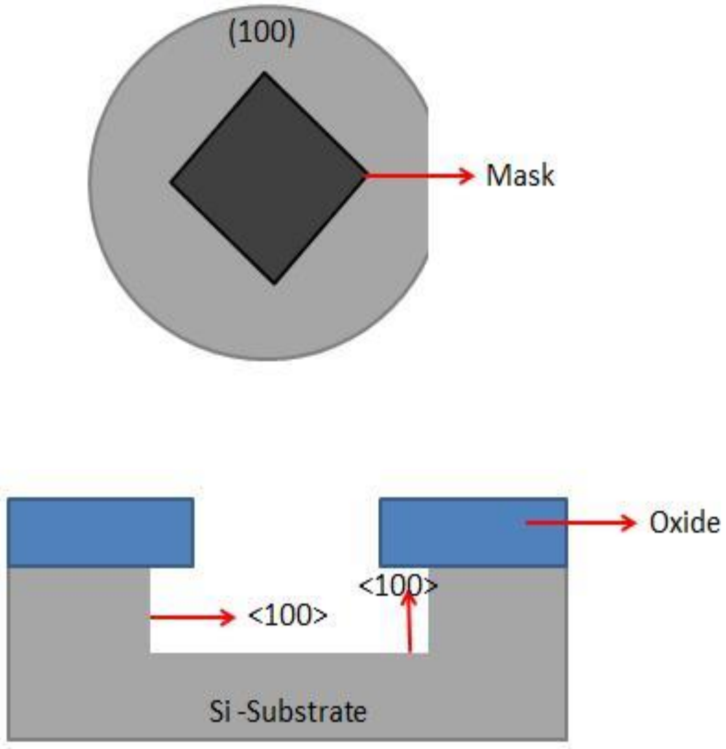
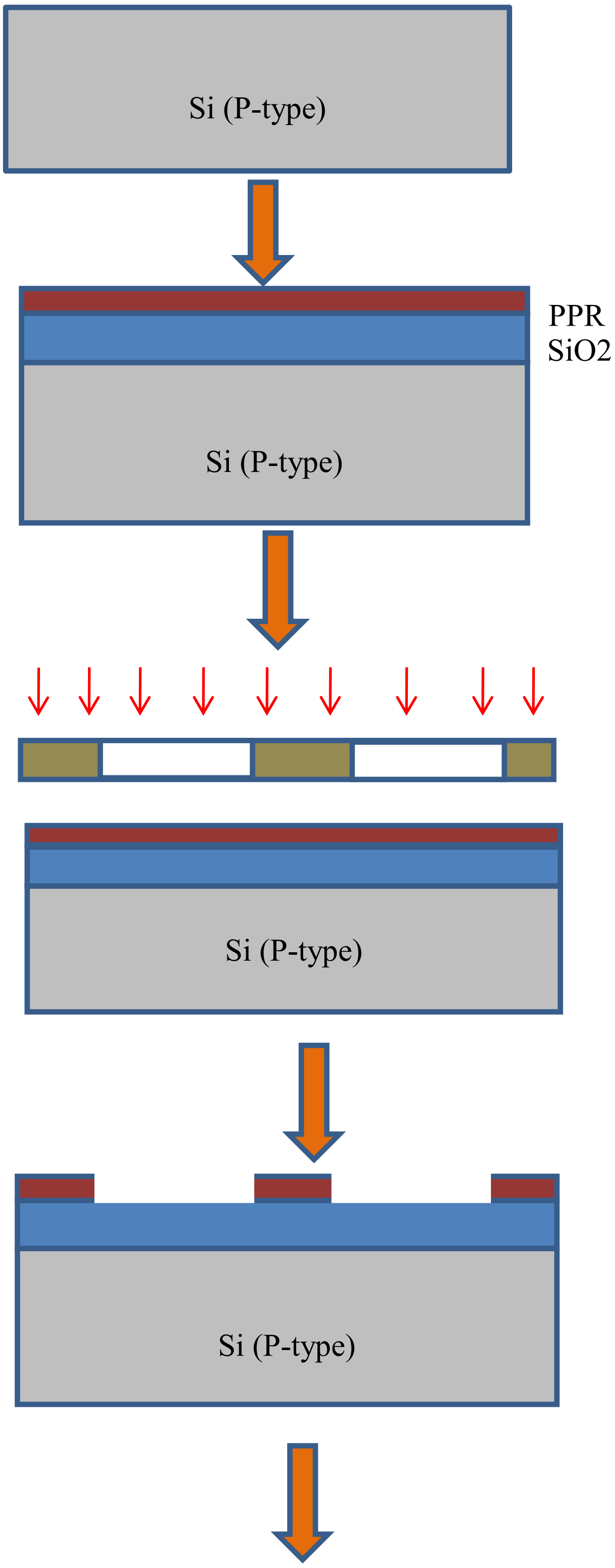
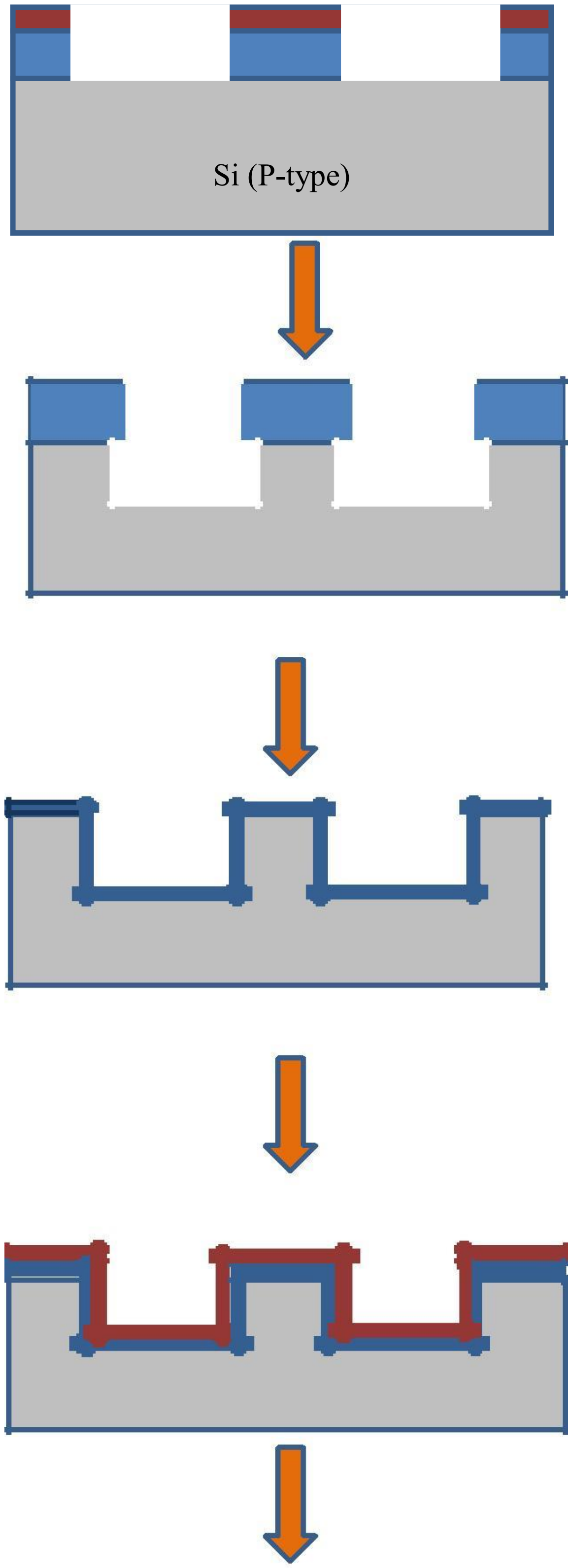


Fig. 3.2: Etched pattern obtained in (100) Si wafer with mask aligned in (100) direction.

3.2 Process Flow for obtaining silicon Microbridge




Si (P-type)

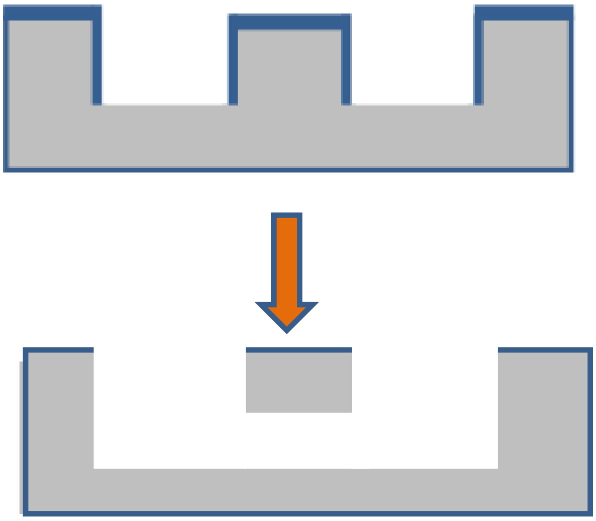


Fig 3.3: Process flow for making Si Bridge

3.3 Results and Discussion

We made the desired mask and carried out the experiment to see the etched profile obtained in (100) wafer, when the mask is in (100) direction. Fig.3.4 shows wafer after 1st etching step and fig.3.5 and fig.3.6 shows optical profilometer images showing the plot of height versus width of the etched pillar obtained after the first etching. If the etching is done in both the direction then by controlling the time of etching and hence etches depth we can have Si cantilevers and bridges in only two step etching process but we need to protect the sidewalls of the etched pillars after first etching step.

We started the process with taking Si (100) wafer, oxidized it where the oxide acts as the etch mask. Made the mask and rotated it by 45° so that while exposing the mask will be in the direction of (100) plane. Then by using anisotropic etchant TMAH we etched the Si to the depth of 8µm. In the subsequent step we cleaned the etched wafer oxidised it. Using the same mask once again we exposed and etched to a depth of 16µm which results in the formation of Si cantilever/Bridge. The above process is simulated in FABSIM which is shown in Fig. 3.7

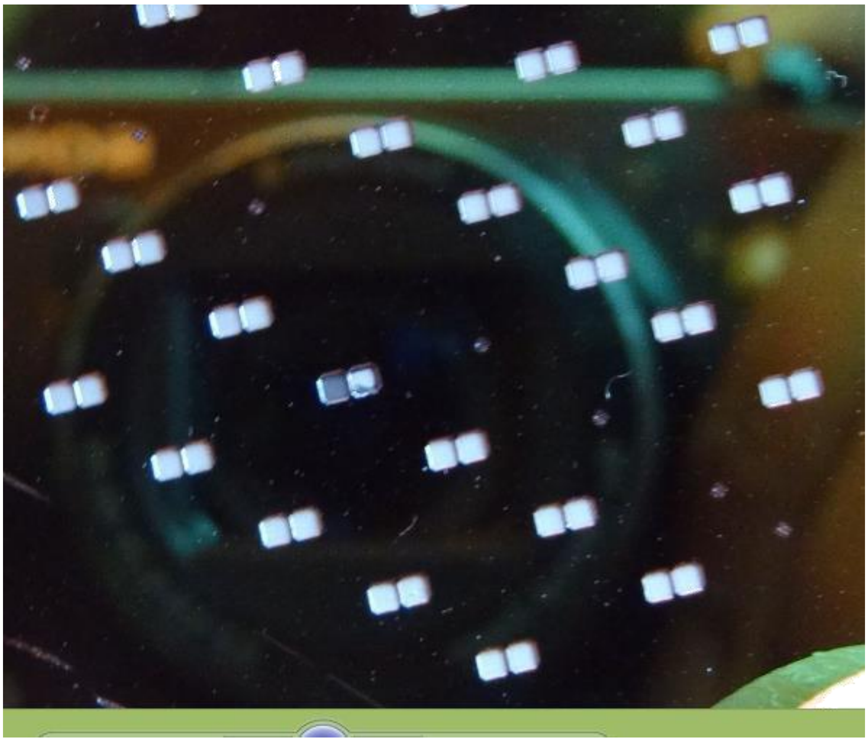


Fig.3.4: Showing wafer after 1st etching step

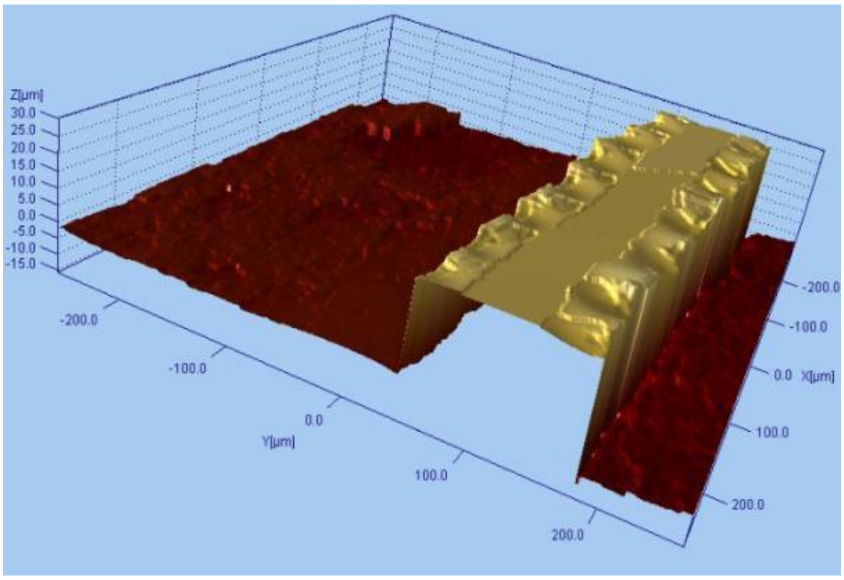


Fig. 3.5: The optical profilometry image of the etched pattern obtained where mask is in (100) direction

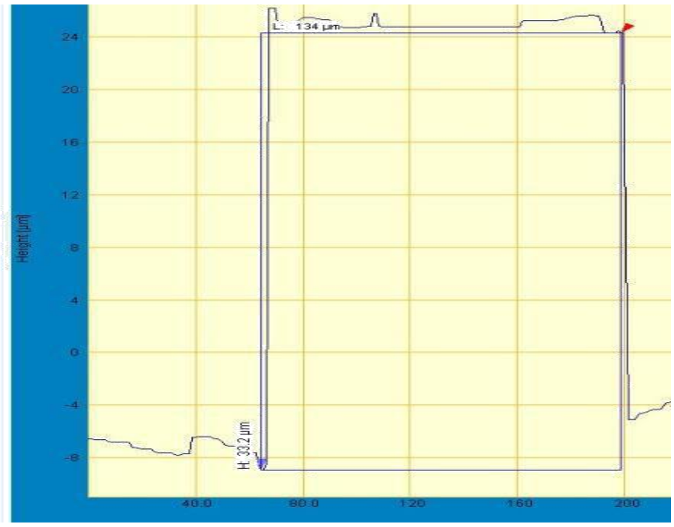


Fig. 3.6: Height and width of the etched pillar after first etching step.

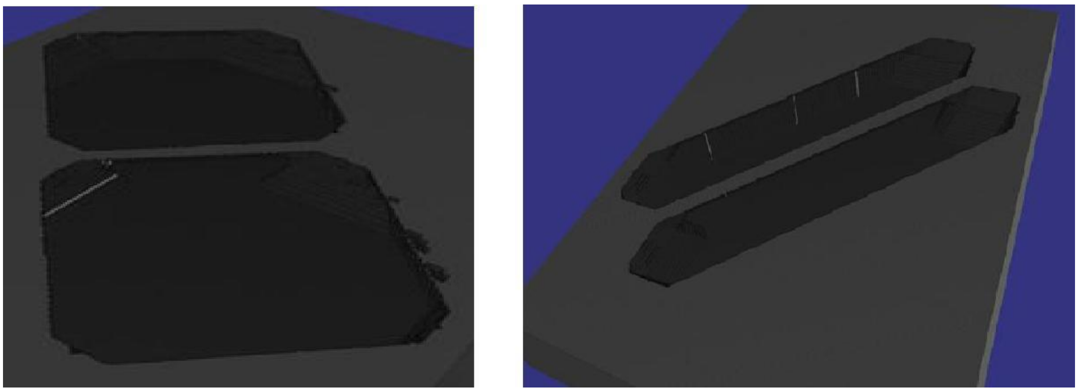


Fig.3.7.FABSIM based physical simulation for making Si micro bridge.

This is the simplest method of making Si microbridges by using only chemical etchant. But as we can observed from the result, for making we are wasting a lot of area being etched outside which is due to opening created by the mask. So to avoid this issue we proposed some area efficient mask designs which is explained in the next section.

Chapter 4

Design and Fabrication Process of Microbolometer

4.1 Innovative method for fabricating Microbolometer

A lot of techniques have been reported so far to fabricate microbolometers and array of it. But all the methods reported have certain drawbacks e.g. pixel form factor, cost and temperature. We are reporting a technique in which the silicon itself is a bolometer sensing material as that in the case of CMOS line bolometer but unlike CMOS type, here the same silicon substrate is used as the sensing material, may be n-type or p-type depending on the substrate we have chosen, hence avoiding the diffusion step which is required for etch stopping in standard CMOS line bolometer. We are targeting to achieve the array of bolometer by 3D integration technique unlike the usual 3D integration where a sacrificial layer is required which may suffer from the reliability issue of being the hanging structure.

Here we are reporting an innovative way of fabricating Bolometer device only by front end bulk micromachining where neither diffusion nor the cumbersome electrochemical etch stopping is required. The thermally insulated membrane achieved can be used as the bolometer sensing material and if we want to increase the sensitivity we can deposit any of the high TCR material such as VOx over the membrane before going for 3D integration with the ROIC. As the membrane itself is the part of the silicon substrate it is going to give much better reliability as compared to the recently developed heterogeneous 3D integration of bolometer.

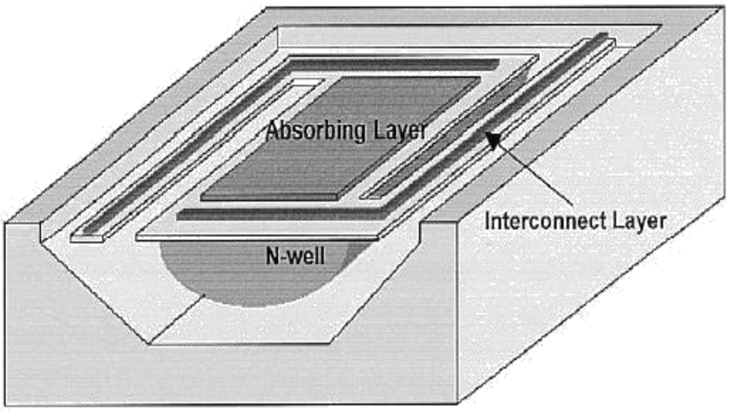


Fig.4.1: Showing the standard CMOS line Bolometer fabrication where n-well is used as the sensing Layer

4.2 Design of Microbolometer

The bolometer design is fundamental stage in the bolometer fabrication. There are numerous of design features and trade-offs which have to be considered. The low thermal conductance between bolometer and its surrounding, the high absorption of the IR radiation including the option of a sensing material with high temperature coefficient of resistance, and low 1/f noise properties, and as low thermal time constant as possible, these are the most important parameters which have to be considered during the bolometer design. Nowadays, the typical size of a commercial pixel is about 17 µm × 17 µm. These sorts of pixels allow achieving the focal plane of high resolution arrays at acceptable cost [11].

The typical bolometer design is shown in Fig. 4.2. Small thermal conductance between bolometer and its surroundings is obtained by using the long bolometer legs. The low thermal capacity is achieved by small cross section area using the materials with low thermal conductivity. There is a metal electrode on the legs which provides the contact between the IR detecting material and the read-out circuit. The modern bolometers have thermal conductivity between legs and substrate typically as low as $3.5\times10_{-8}$ W/K. There is a need to minimize the thermal convection between the bolometer and its surroundings so the conventional bolometer chips are in vacuum package with pressure in the order of 0.01 mbar (1 Pa).

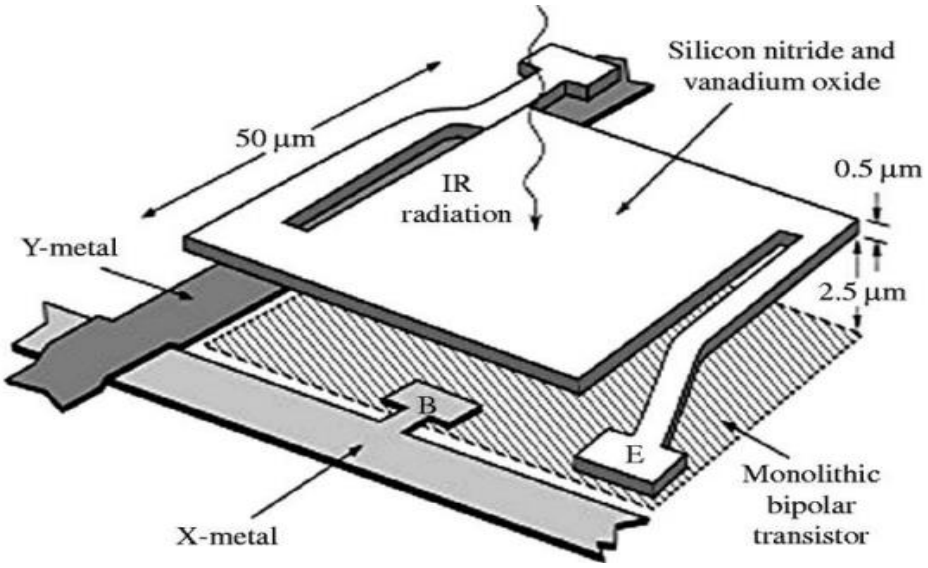
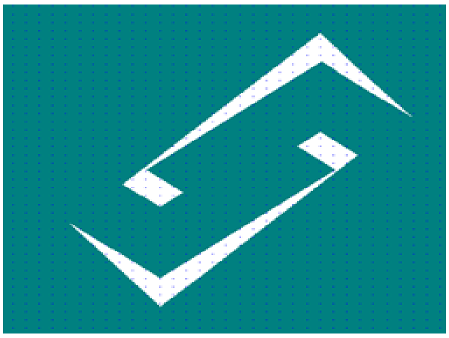


Fig.4.2 Typical Bolometer structure

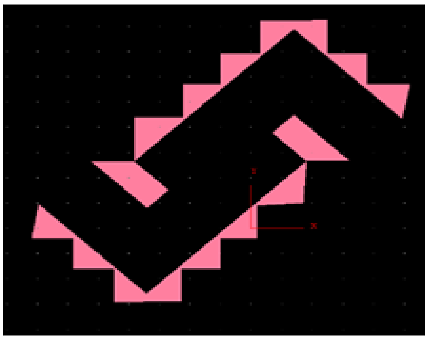
The proper mask was designed for the fabrication of bolometer after doing various simulations on Intellisuite FABsim based Physical Simulator .The above parameters were kept in mind while designing different bolometer structures. The basic structure of the bolometer is shown in fig.4.3.

Fig.4.3. Mask used for bolometer sensor memebrane

The mask used to make the microbolometer sensor is made up of all rectangular areas which when exposed on Si wafer will open all the (100) planes insides as well as outside. Due to which we will not only having undercut inside but also will lose area outside which need to be prevented. More the area consumed by the sensor less will be pixel fill factor. So to reduce the area consumption we have made some designs which will allow the etchant to enter only in the desired direction and prevents unnecessary area consumption in all other directions. Those mask designs are useful in both the methods of fabricating the microbolometer sensor which has described neatly in the below subsections. We have proposed four mask designs to reduce area consumed per pixel of microbolometer sensor. Same concept has been applied to make area efficient microbolometer as that of making area efficient Si microbridges. Below are the details of all mask designs.

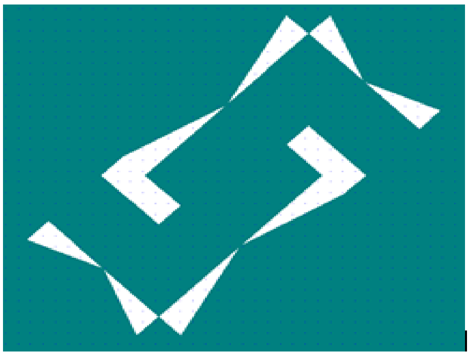


Design-2



Design-3

Design-4



Design -5

4.3 Fabrication Process Flow of Microbolometer

We adopted mainly two fabrication processes for microbolometer sensor. One involving only wet etching of Si and in the other, dry etching followed by wet etching. Both the processes have been described here. In both the methods, we started with oxidized Si wafers, made the desired mask for bolometer sensor and rotated it by 45° before printing as the primary step. Every part of the mask is nothing but a rectangular structure, so rotating it with 45^o and putting in TMAH will result in vertical etching , as all the (100) planes are exposed inside.

4.3.1 Using only wet Etching

Fabrication using only chemical etching started with a basic bolometer design as aforementioned. To make the process more cost effective only one mask is used in the entire process. At first we exposed the spin coated Si wafer with the mask and etched for 16um using Tetra methyl ammonium oxide (TMAH). Then the resulting etched wafer is put in oxidation chamber to get oxidized. As the TMAH etching is done both in horizontal as well as vertical direction, etching started exposing the (111) planes as it goes in horizontally, those exposed (111) planes creates problem by restricting the etching in that direction. So we have removed these exposed (111) planes using isotropic etchant HNA ($CH_3COOH+HNO_3+HF$) by etching to a depth of 5um. After isotropic etching the wafer is cleaned and then again oxidized. Now in the final step the resulting etched Si wafer is again etched using anisotropic wet etchant TMAH, which results in the formation of freely standing isolated membrane which can be used as the sensor for microbolometer. In the whole process we have used only one mask for all Lithography process to expose UV light. The process flow of the above method is shown in the fig.4.4.

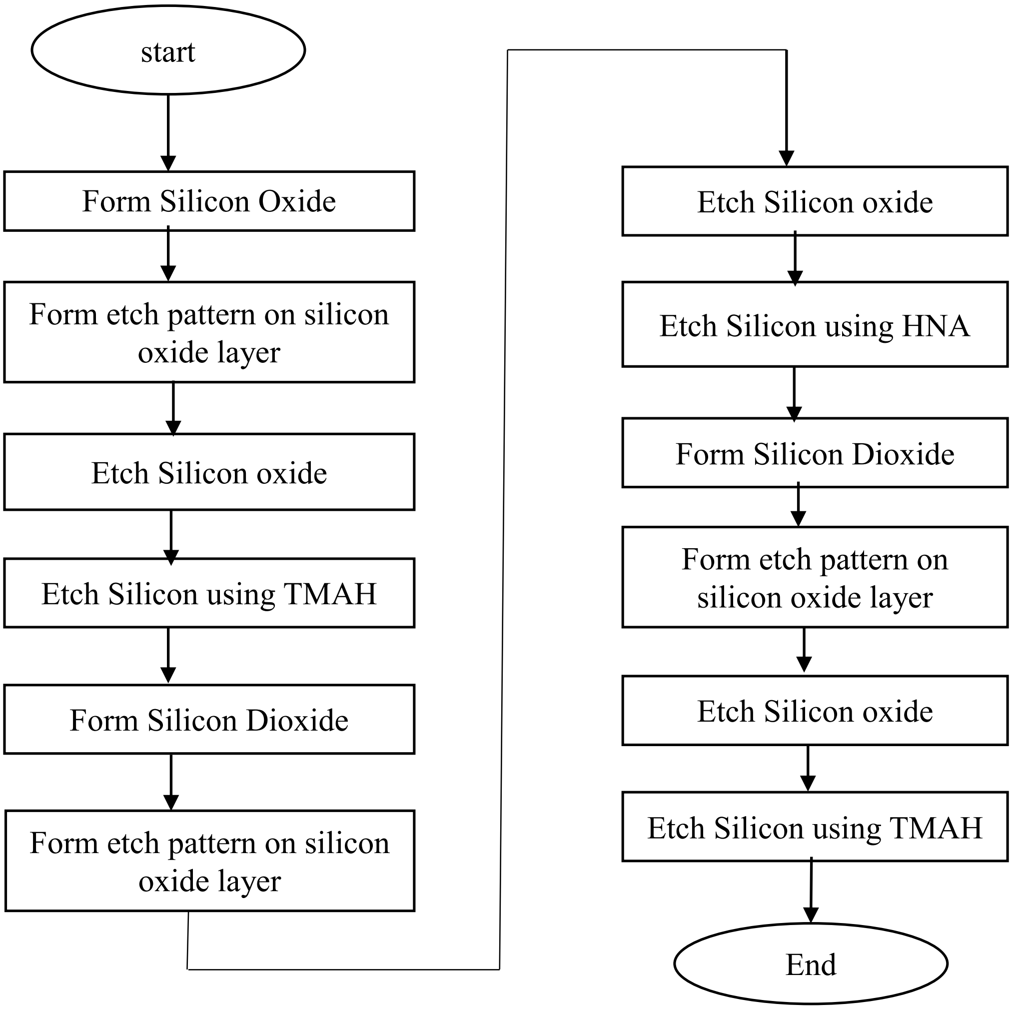


Fig.4.4: showing process flow to obtain microbolometer sensor.

4.3.2 Using Dry and wet Etching

In this method of making microbolometer sensor, Dry etching (Xenon Fluoride) was adopted instead of HNA etching. Here we started with the same mask as we used in the above process. In first step spin coated Si substrate was exposed with the mask and etched around 20um depth using TMAH. Then the resultant etched wafer put in oxidation chamber to get oxidized. Now again using the same mask silicon was exposed and etched around 20um depth using XeF2 which has very high selectivity with Sio2.The main advantage of this step over HNA etching is it won't effect oxide layer which we are using for protecting side walls and at the same time we are etching more depth using this method so we can easily release hanging structure in the third step. After isotropic etching the wafer is cleaned and then again oxidized. Now in the final step the resulting etched Si wafer is again etched using anisotropic wet etchant TMAH, which results in the formation of freely standing isolated membrane which can be used as the sensor for microbolometer.

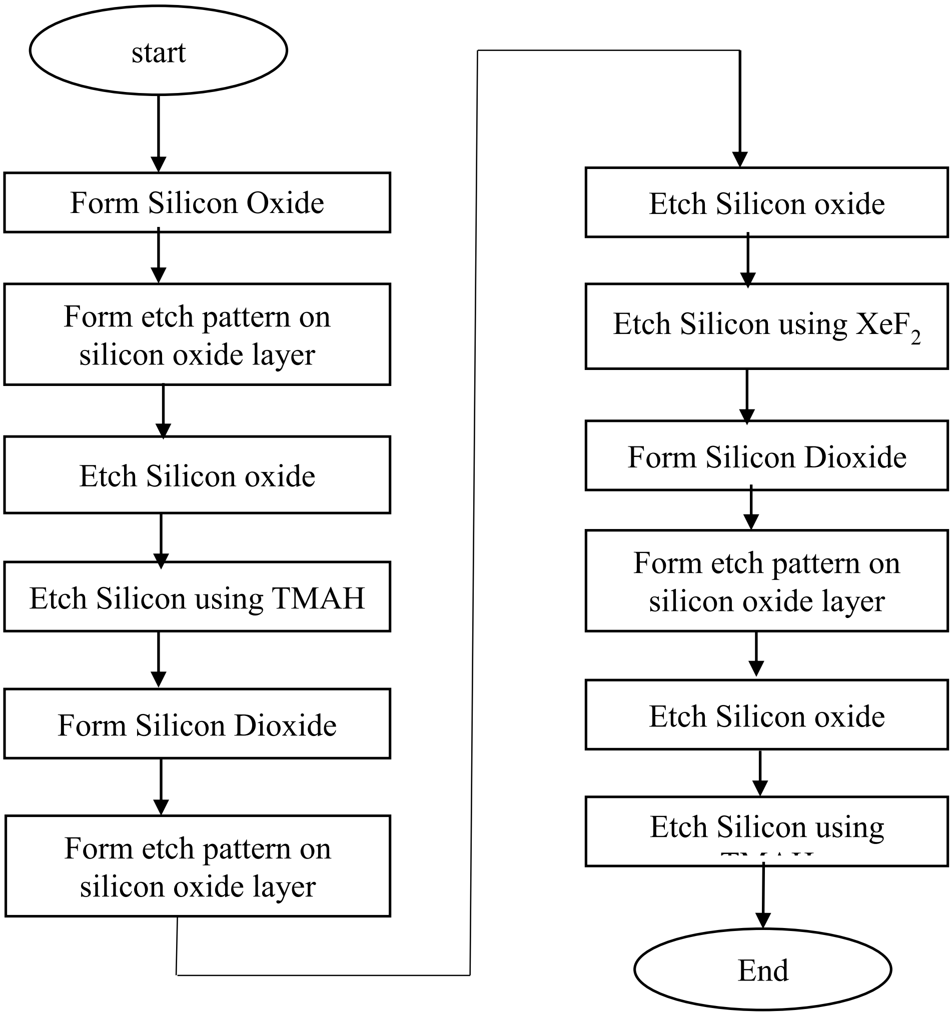


Fig.4.5: Showing process flow to obtain Microbolometer sensor using above method

Chapter 5

Results and Discussions

5.1. Anisotropic (TMAH) Etching

The microbolometer is fabricated using the mask as shown in the previous chapter. The fabrication process is followed as per the simulation results achieved in the Intellisuite Fabsim. The process followed for micro bridges and microbolometer is almost same except for one extra step (HNA etching) in the fabrication of microbolometer. We will discuss the difference in the coming sections.

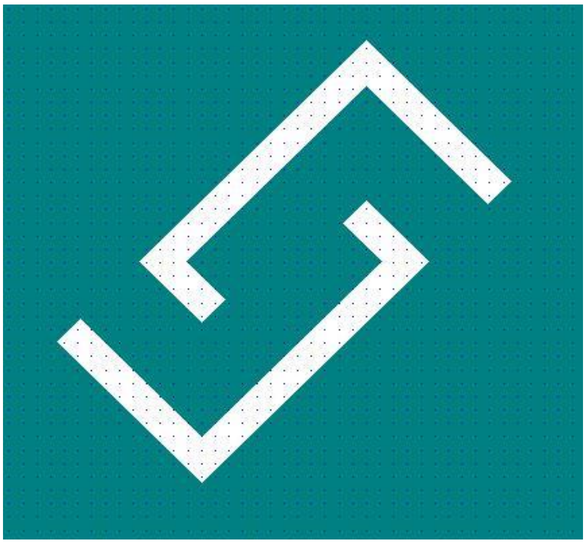
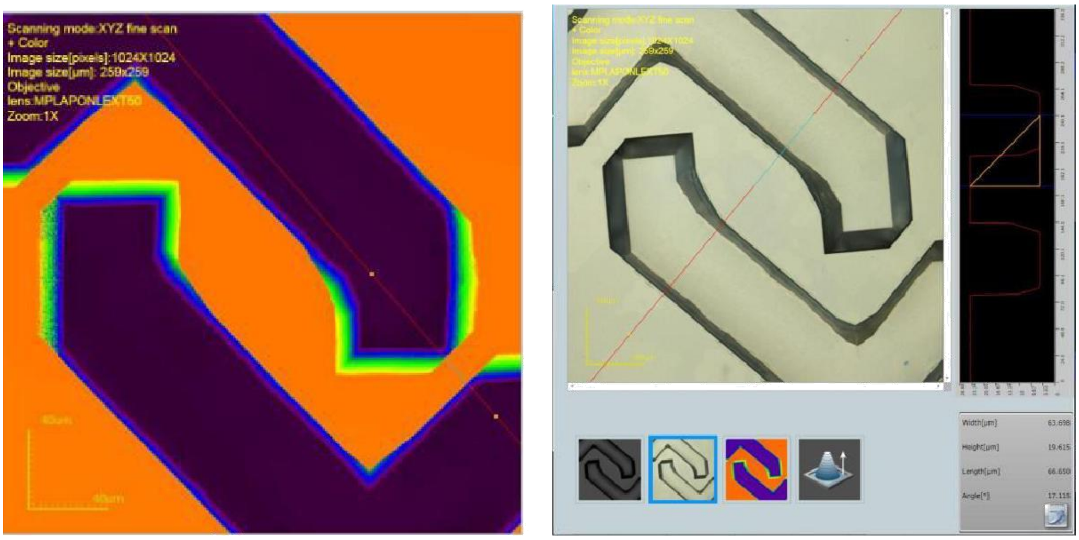


Fig.5.1 shows the basic mask design for fabricating bolometer.

Figure 5.1 shows the mask used for the fabrication of bolometer. Using this mask the oxidized wafer was patterned and oxide was removed selectively in Hydrofluoric Acid (HF) and further the exposed silicon was etched in TMAH. Using S1813 photo resist, we could achieve the proper etching and required profile after the first step. The etch profile is shown in the fig.5.2 after silicon etching using TMAH. It shows both contour and cutline of etched profile.


Scanning mode:XYZ fine scan
+ Color
Image size[pixels]:1024X1024
Image size[μm]: 259x259
Objective
lens:MPLAPONLEXT50
Zoom:1X

Width[μm] 63.698
Height[μm] 19.615
Length[μm] 66.650
Angle[°] 17.115

(a) (b)

Fig 5.2 (a) shows contour plot of the etched bolometer after first step. (b) Shows the profile of the etched silicon after the first step.

The first step lithography was done using low vacuum mode in the lithography system which will make the mask and wafer in contact. This will help us achieve the same dimensions of the mask on the wafer since the diffraction of light is minimized.

After etching silicon in first step we prepared the same sample for second step by cleaning and oxidizing the wafer. When proceeded for the second step, the problem now aroused is that the side wall protection. When we spin the positive photo resist, the device should be protected from top and sideways. Due to the less viscosity and the uneven device structure, we could not protect the top surface of the structure. To overcome this problem we went for thick photoresist which can solve our problem. Thick photo resist has high viscosity and forms a thick layer of photoresist when spun. A thickness of approximately 12 µm is achieved using this thick photoresist. We used AZ4620 thick photoresist to overcome this issue. We exposed the sample for 102 sec at the lamp intensity of 4 as per the data sheet of the photoresist. The developer used is AZ400K. Diluted the developer in the ratio of 1:3 (Developer: DI water).

Thus using the thick photoresist, the top surface and the sidewalls were protected properly. The lithography was done and the required area was exposed in the trench. The oxide was removed and proceeded for further steps.

5.2 Isotropic Etching

After the first step we are going for isotropic etching in the second step for the following reason. The difference in the fabrication of micro bridges and micro bolometers is an extra step of isotropic etching. This results due to the structure and the shape of the mask design that we use here. In case of micro bridges it is only a one-dimension. In bolometer there are both concave and convex edges encountered during the etching process. The concept explained in the initial chapters about the 45^0 rotation is valid but with some restrictions. When we create a rectangular/square opening with edge at 45^0 to the wafer flat, the etch profile of the silicon will be perpendicular and not a 54.7^0 tilt. The etchant will not be able to see the 111 plane and so it etches perpendicularly. But this happens only at the middle of the line (edge). At the edges the etchant will face 111 plane and will not be able to etch perpendicularly. When such processed sampled, after creating a square pattern (aligned at 45^0 to wafer flat) etched for long time will create a square structure super scribing the initial square and with a pyramid structure. This is same as patterning a square parallel to the wafer flat.

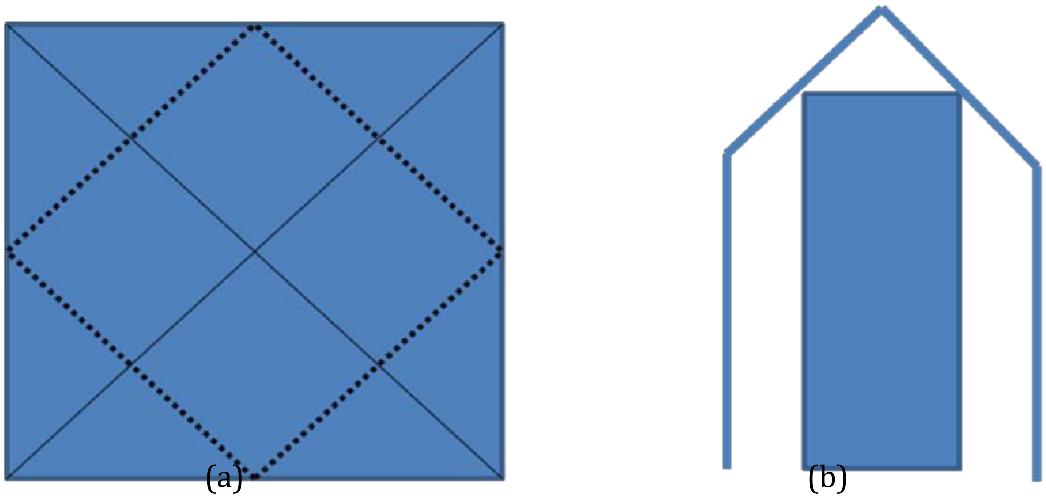


Fig.5.3 (a) Shows the etch profile of silicon when etched in TMAH with openings aligned 45^0 to the wafer flat. (b) Etch profile observed in the bolometer structure.

This issue is seen while fabricating the bolometer at the concave edges. So to avoid this issue we go for isotropic etching to etch all the planes. This will remove the hurdle of 111 planes and clears the obstacle for the next TMAH etching.

One more reason for isotropic etching is that, the TMAH etching will lead to a super scribing square when a square with 45^0 angle is etched for sufficiently long time. So at the concave edges while etching the bolometer structure, the same phenomenon is observed. When the same mask is used for the second time, the edges (as shown in the figure) get exposed and the top surface is not protected. So when the sample is put in TMAH for etching, it starts to etch from the top surface also which is not desirable.

5.2.1 HNA Etching (Wet etching)

Once the lithography is over for the second step, HNA etching was done to break the (111) planes as explained previously. HNA etching is isotropic and etches in all directions. The profile of the etched silicon after HNA etching is shown in the fig 5.4. This will not only help in eliminating the 111 planes but also in realizing the proper shape of the bolometer sensor. The HNA etchant was prepared in the ratio of 11:7:4 as Acetic Acid: Nitric acid: HF.

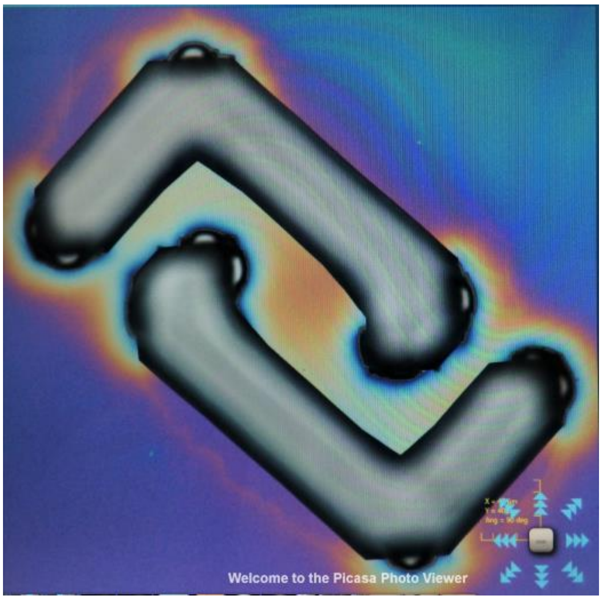


Fig.5.4 Shows Fabrication result after HNA etch

5.2.2 XeF_2 Etching (Dry Etching)

Unlike HNA here we used XeF_2 for isotropic etching which is physical etching to etch silicon. The problem we are facing with HNA etching is the selectivity problem of silicon and silicon oxide which is very less, so there we can’t go for more time to etch silicon to achieve reasonable depth. Here by using physical etching we can easily solve as aforementioned problems and at the same time we can etch more depth which will be very useful to release hanging structure in next step using TMAH. Here we etched silicon approximately 20um after first step. Fig.5.5 shows the etched profile of the bolometer after XeF_2 etching.

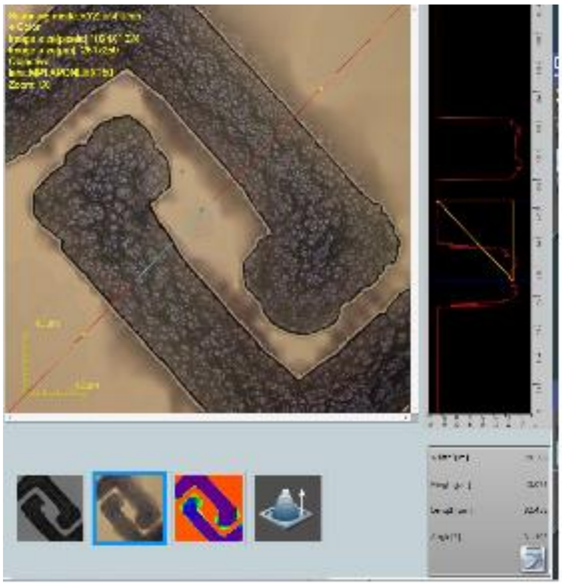


Fig.5.5: Shows the fabrication result after XeF_2 etching

5.3 Sensor membrane (Hanging structure)

Again the existing oxide is removed and oxidized the processed wafer for further steps. After oxidizing, again the photoresist is spun and patterned using lithography and oxide is etched selectively in the trenches and put in TMAH for further etching. This final step etching will release the hanging structure. All the etchings are calculated and done according to the data obtained from the simulations. The TMAH was used in the ratio of 2:3 TMAH: DI water. The silicon etching in TMAH was done at 75^0C. The etch rate is approximately 0.8-1 µm/min at 75^0C. A proper careful and calculated etching is required to take care that the sensor membrane is neither over etched nor etched less.

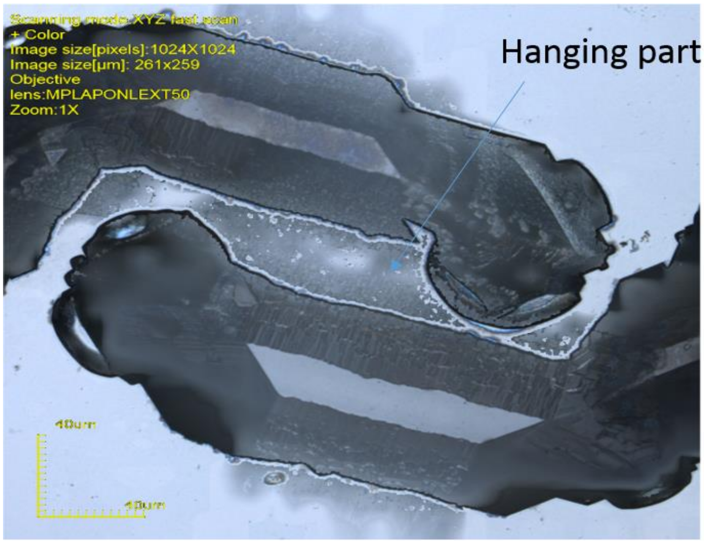


Fig: 5.7(a) Shows the Fabrication result after TMAH etch using only wet etching (here in figure we can see the hanging membrane which is almost transparent)

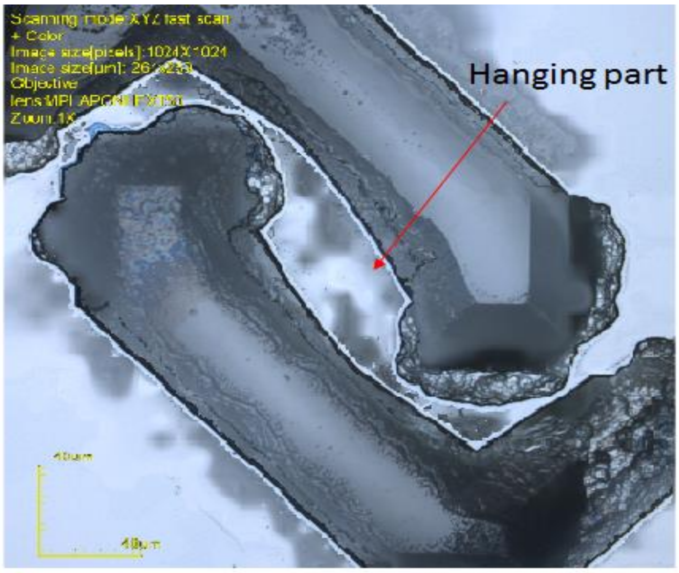


Fig: 5.7(b) Shows the Fabrication result after TMAH etch using wet and dry etching (here in figure we can see the hanging membrane which is almost transparent)

5.4 Voltage-Current (IV) Measurements of the Hanging Structure

Here we have done IV measurements using keithley 4200 SCS instrument, where we swiped voltage from 0 to 5 volts between the two legs of the device and from that we have extracted the resistance value of the membrane. Using IR source meter we varied the membrane temperature from 30°C to 90° C and here we observed the resistance value. Here the membrane of the device is silicon so the resistance value of the device is decreasing with increasing temperature and it is increasing with decreasing temperature. Fig 5.8 shows the graph of the IV characteristics at different temperatures and fig 5.9 shows the resistance value of the membrane at different temperatures.

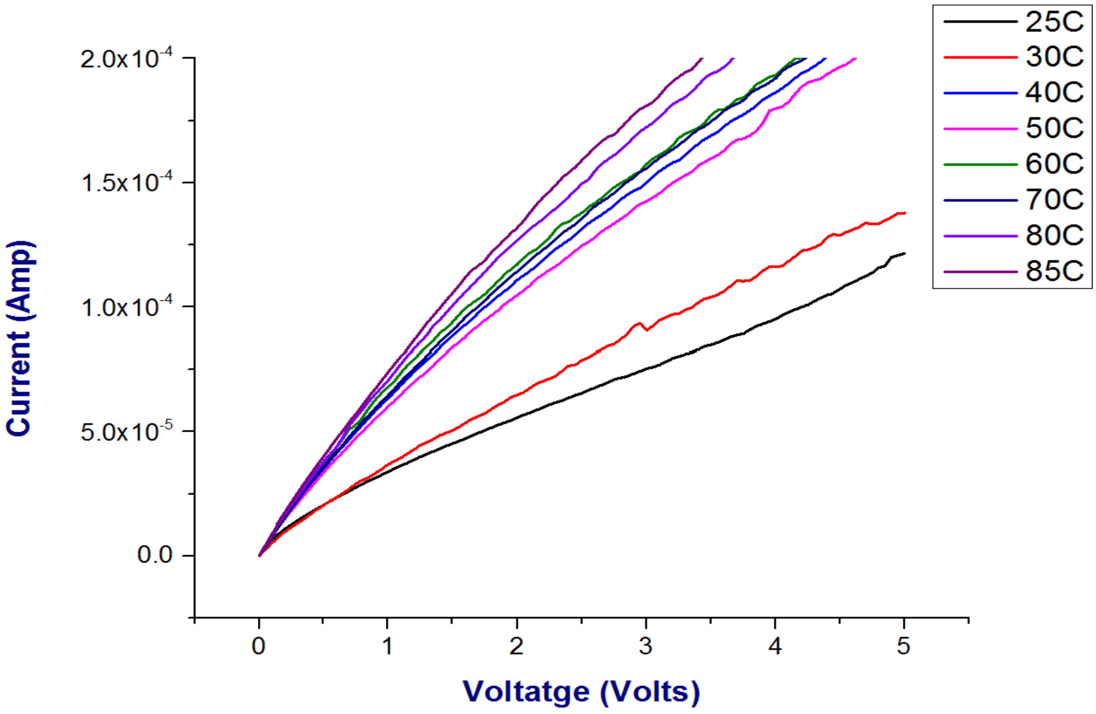


Fig.5.8 Shows the IV characteristics of sensor membrane at different temperatures

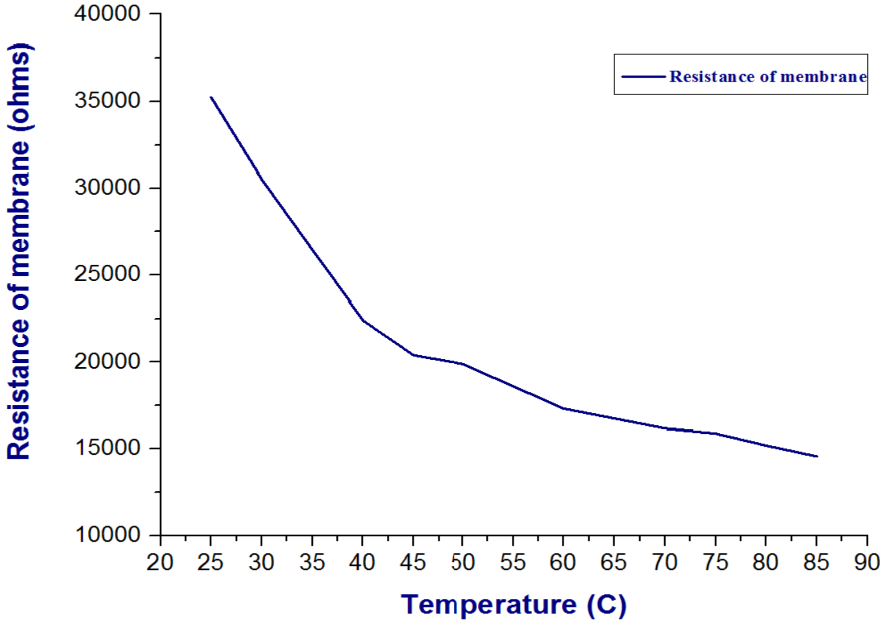


Fig.5.9 shows the resistance of the membrane at different temperatures

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In the present work we have proposed cost effective and novel way to make microbolometer sensor as well as Si microbridges. Where the proposed method of making Si Micro bridges or cantilever beams is based on two simple techniques i.e. the frontend bulk micromachining which reduces the requirement of clean room and hence the cost associated with it. The efficient mask deigns proposed decreases foot print of individual pixels hence increases overall efficiency of the device which may be simple Si micro bridge or cantilever or any of the complicated structure or may be array of any of the above.

The methods proposed in the work to fabricate microbolometer sensor are simple and majorly consists of etching steps only. These methods doesn’t require any diffusion or electrochemical etch stopping technique, which may complicate the process. The first proposed method i.e., by using only wet etching avoids the requirement of clean room which can reduce the cost of making the device. The second method i.e. by using both dry and wet etching can reduce the cost and at the same time it is giving better stability and proper shape of the device which can be very useful during characterization of the device.

6.2 Future work

The present work was focused to make microbolometer sensor in a simple and cost effective way. The scope for the future work is listed below.

- Optimization and characterization of the microbolometer sensor.
- Isolation of the device with the substrate for proper measurements and better sensitivity.

- Deposition of high TCR microbolometer sensing material
- Mirror material deposition at bottom of the sensor for capturing more IR radiations.
- 3D integration of microbolometer sensor with its corresponding ROIC.

References

[1] A.Schaufelbuhl,“Thermal Imagers in CMOS Technology”, *Dissertation for the Degree of Doctor of Philosophy*, PEL, ETH Zurich, 2001.

[2] P.W. Kruse, *Uncooled Thermal Imaging Arrays, Systems, and Applications*, SPIE Press, 2001.

[3] ROGALSKI, A. Infrared detectors: an overview. *Infrared Physics & Technology*, 2002, vol. 43, no. 3–5, pp. 187-210. ISSN 1350-449.

[4] Darius Jakonis, Christer Svensson , Christer Jansson “Readout architectures for uncooled IR detector arrays” *Sensors and Actuators* 84 _2000. 220–229.

[5] Gregory T. A. Kovacs, Member, IEEE, Nadim I. Maluf, Member, IEEE, and Kurt E. Petersen, Fellow, IEEE “Bulk Micromachining of Silicon” , VOL. 86, NO. 8, AUGUST 1998

[6] Frank Niklaus, Christian Vieider, Henrik Jakobsen “MEMS-Based Uncooled Infrared Bolometer Arrays – A Review” MEMS/MOEMS Technologies and Applications III, III, edited by Jung-Chih Chiao, Xuyuan Chen, Zhaoying Zhou, Xinxin Li,Proc. of SPIE Vol. 6836, 68360D, (2007).

[7] .Selim Eminoglu, Deniz Sabuncuoglu Tezcan, M. Yusuf Tanrikulu, Tayfun Akin “Low-cost uncooled infrared detectors in CMOS process” Department of Electrical and Electronics Engineering, Middle East Technical University, Ankara 06531, Turkey. Sensors and Actuators A 109 (2003) 102–113.

[8] Deniz Sabuncuoglu Tezcan*, Selim Eminoglu", Orhan Sevket Akar**, and Tayfun .Akin*,* Department of Electrical and Electronics Engineering, Middle East Technical University, Ankara, Turkey “A Low Cost Uncooled Infrared Microbolometer Focal Plane Array Using The Cmos N-Well Layeir” ** TUBITAKBILTEN, Middle East Technical University, Ankara, Turkey.

[9] Ben Kloeck, Scott D. Collins, Nico F. De Rooij, And Rosemary L. Smith “Study of Electrochemical Etch-Stop for High-Precision Thickness Control of Silicon Membranes”, *IEEE Transactions On Electron Devices*. VOL. 36. NO. 4. APRIL 1989.

[10] Frank Niklaus, Adit Decharat, Fredrik Forsberg , Niclas Roxhed , Martin Lapisa, Michael Populin ,Fabian Zimmer, Jörn Lemmb, Göran Stemme “Wafer bonding with nano-imprint resists as sacrificial adhesive for fabrication of silicon-onintegrated-circuit (SOIC) wafers in 3D integration of MEMS and ICs” *Sensors and Actuators* A 154 (2009) 180–186.

[11] FRANK NIKLAUS, C. V., HENRIK JAKOBSEN MEMS-Based Uncooled Infrared Bolometer Arrays – A Review. *MEMS/MOEMS Technologies and Applications* III, 2007, vol. 6836, pp. 15.

[12] Conference Proceedings KIMATA, M. MEMS-Based Uncooled Infrared Focal Plane Arrays. *Solid-State Sensors, Actuators and Microsystems Conference*, 2007. TRANSDUCERS 2007. International. 10-14 June 2007.

[13] “Uncooled Infrared Detectors Achieve New Performance Levels and Cost Targets”,Sofradir.EC.Inc.

[14] Ben Kloeck, Scott D. Collins, Nico F. De Rooij, And Rosemary L. Smith “Study of Electrochemical Etch-Stop for High-Precision Thickness Control of Silicon Membranes” *IEEE Transactions On Electron Devices*. VOL. 36. NO. a.APRIL 1989.

[15] Ei-no H. Klaassen *, Richard J. Reay, Christopher Storment, Gregory T.A. Kovacs Center fi~r bttegrated Systems. CIS-X 202. Stanford Univerm~'. Stanford, CA 94305-4075 USA “Micromachined thermally isolated circuits” Sensors and Actuators A 58 (1997) 43-50.

[16] M.C. Acero, J. Esteve, Chr.Burrer, A. Gotz “Electrochemical etch-stop characteristics of TMAH:IPA solutions “ Sensors and actuators A46-47(1995) 22-26.

[17] Ernest Bassous “Fabrication of novel Three- Dimensional microstructures by anisotropic etching of (100) and (110) Silicon” IEEE Transactions on Electron Devices, Vol. ED-25, NO.10 October 1978.

[18] .E.chen Applied physics 298r.

[19] Weileun Fang “Design of bulk micromachined suspensions” J.Micromech.Microeng. 8 (1998) 263–271.

[20] R.A.Wood,“Uncooled Thermal Imaging with Monolithic Silicon Focal Arrays,” Infrared Technology XIX, Proc. SPIE Vol. 2020, pp. 322-329, 1993.

[21] Selim Eminoğlu ,“Uncooled Infrared Focal Plane Arrays With Integrated Readout Circuitry Using Mems And Standard Cmos Technologies”, Dissertation for the Degree of Doctor of Philosophy, the graduate school of natural and applied sciences of the middle east technical university.

[22] Bc. VOJTĚCH SVATOŠ, “Design And Simulation Of Micro-Bolometer In Mems Technology”,Disserattion for the Degree of Master’s,Brno University of Technology.

[23] Radharaman Mohanty,” Realizing Area efficient Silicon Micro Structures Using Only Front End Bulk Micromachining” International Journal of Advances in Engineering Sciences and Applied Mathematics December 2015, Volume 7, Issue 4, pp 191-197