# SILICON MICROTIPS WITH SELF-ALIGNED INTEGRATED ELECTRODES

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In this work we present a method for the fabrication of silicon microtips with self-aligned anodes in order to obtain field emitting devices. The method is based on the anisotropic corrosion of the silicon substrate in KOH solutions and utilizes low stress $SiO_xN_y$ films obtained by PECVD as masking material. These films are also utilized as structural material for mechanical support and electrical insulation of the electrodes. For the electrodes sputtered Cr films are utilized. Optical microscopy was utilized to determine the etch rate of the different stages during the microtip formation, in order to enable us to ascertain the total development time versus the initial mask dimensions. Matrixes with different number of microtips, 52 μm height and with diameter at the vertex bellow 1 μm, were fabricated and characterized. The results also show that the low stress $SiO_xN_y$ film is essential to endure the corrosion process without structural damage.

## Introduction

In the last years the development of Micro Electro-Mechanical Systems (MEMS) has received increasing attention, which at the same time has led to the development of a variety of sensors, actuators and microstructures for very different areas (1,2,3). Among these microstructures, silicon microtips are one of the more interesting due to the possibility of fabrication low voltage electron field emitting devices. In this way, Si microtips exhibit a vast field of applications in the so called Vacuum Microelectronics, specially for field emission displays (FED's), electron beam lithography, microwave power amplifiers, tips for atomic force microscope AFM, and so on (4,5,6).

Different approaches have been reported for the fabrication of Si microtips but the simplest techniques are based in bulk micromachining of the Si substrate (7). For example, wet anisotropic etching in alkaline solutions, mixed or not with dry isotropic corrosion steps, and followed by thermal oxidation sharpening have been utilized to fabricate silicon tips with excellent geometry and size in the range of a few microns and smaller (8,9). Other processes utilize porous silicon as sacrificial layer in isotropic wet etching, also in alkaline solutions, and with similar results (10). All these processes are simple but have the inconvenience that the polarization electrode must be positioned externally, through manually operated micromanipulators with resolution in the micron range.

In that way and motivated by the simplicity of silicon micromachining in alkaline solutions, here we present a method for the fabrication of silicon microtips with self-aligned integrated electrodes on (100) oriented Si wafers.

***Materials and Process***

The method proposed here is based on the under-etch observed when an anisotropic Si etching is carried out (in KOH solutions) trough a mask oriented 45$^o$ related the [110] direction in (100) Si wafers. In other words, the microtips are formed under the masking material. In this way, if the masking material had appropriated structural and mechanical properties, it can be utilized also to mechanically support the integrated electrodes, which at the same time, will result self-aligned to the microtips. For this reason is essential to utilize a low stress material that preserves its mechanical stability and flatness after the Si corrosion in KOH.

Due to its low resistance to KOH solution and relatively high internal stress, which leads to non-flat self-sustained films, silicon dioxide ($SiO_2$), a common masking material for Si etching, is not an appropriated choice. So, in this work we utilize thick low stress silicon oxynitride films ($SiO_xN_y$) obtained by Plasma Enhanced Chemical Vapor Deposition (PECVD) at low temperature (~320°C). In fact in recent years we have optimized the deposition conditions to obtain silicon oxynitride films ($SiO_xN_y$) with properties especially suitable for MEMS development. In particular, these films can be easily removed in HF, present high resistance to KOH solution and exhibit very low internal mechanical stress (11,12). So, in previous works (13,14) we have utilized back side Si bulk micromachining technique to fabricate self-sustained grids and membranes (flat and corrugated) of $SiO_xN_y$ with large areas, up to ~1cm$^2$.

For the application described here, $SiO_xN_y$ films also exhibit good dielectric properties. In fact, to observe electron field emission conductivity in the polarized microtips is necessary to remove any other conduction mechanism or leak currents. So, is essential to guarantee the electric insulation between the Si substrate (where the tips are fabricated) and the integrated suspended electrodes. So, the method proposed here depends critically on the superior chemical resistance, mechanical strength and electrical properties of our PECVD $SiO_xN_y$.

The electrodes are obtained by depositing a film of Chromium, which, due to its resistance to KOH, can be deposited before the Si tips formation and does not require any protection step. This is important to simplify the microtips fabrication process.

## Experimental Procedures

The sequence of fabrication steps is shown in Fig.1. The process starts with the deposition of a 1.8 μm thick low stress $SiO_xN_y$ film obtained by PECVD at 320 $^o$C on (100) oriented Si wafer (Fig. 1a). After that, is deposited a 3500 Å film of chromium (Cr) obtained by magnetron sputtering and the electrode geometry is defined by conventional photolithography (Fig. 5b and c). The next step is a photolithographic process to open square holes inclined 45º (related to [110] direction) in the $SiO_xN_y$ film (Fig.1d). After this, is carried out a front side anisotropic wet etching of the Si wafer in a KOH solution (28.7%, 80ºC) to form the Si microtips (Fig.2).

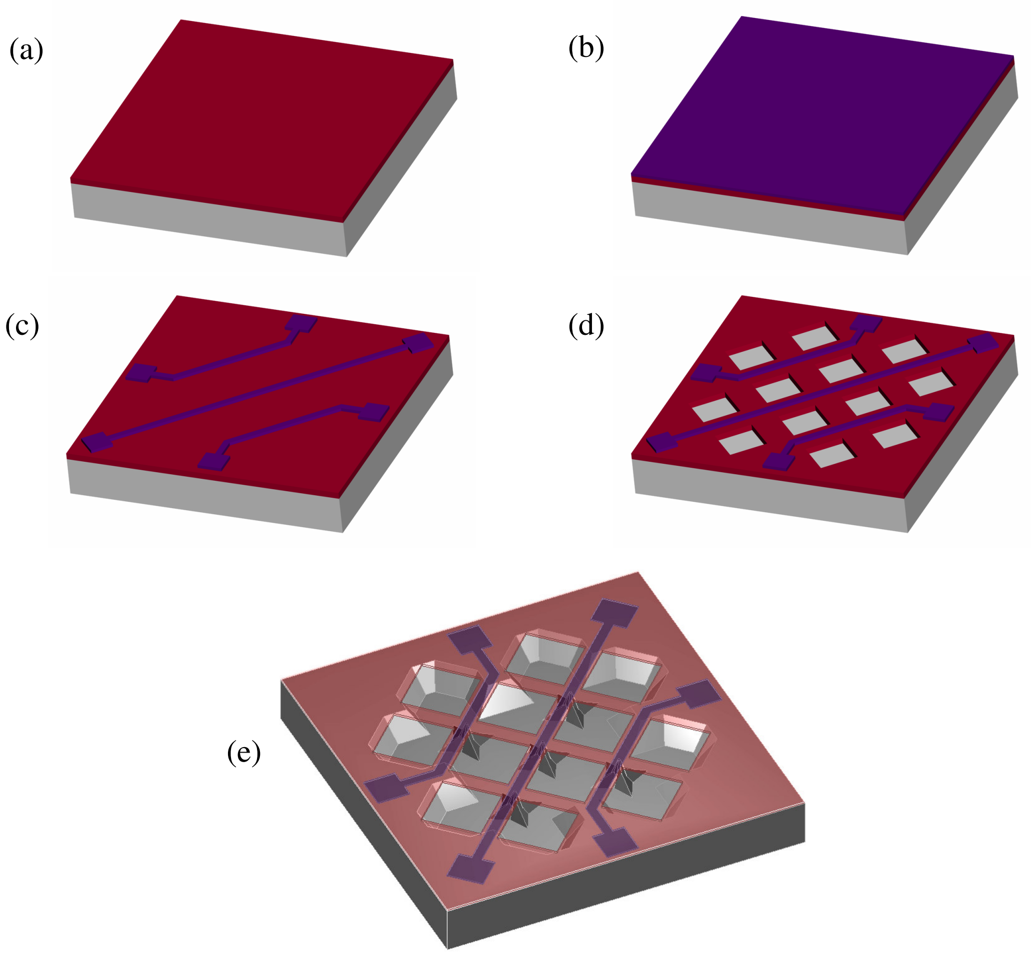


Fig.1. Steps sequence to produce the Si microtips : (a) Deposition of a 1.8 μm thick low stress PECVD $SiO_xN_y$ film and (b) of a 3500 Å film of chromium. (c) Electrode geometry is defined and (d) the square holes (inclined 45º) are open in the $SiO_xN_y$ film. (e) Si microtips formation after de anisotropic wet etching in KOH solution

In this process the silicon oxynitride film ($SiO_xN_y$) has a very important rule since, after the tips formation will give mechanical support for the Cr electrode. In that way, is essential for the $SiO_xN_y$ film to preserve its mechanical stability, structural integrity and flatness. The deposition conditions to obtain $SiO_xN_y$ films with the necessary high resistance to KOH corrosion and low internal stress were optimized in previous works. The films are deposited from appropriated gaseous mixtures of silane ($SiH_4$) and nitrous oxide ($N_2O$) in a conventional capacitivelly coupled r.f. PECVD system. The deposition temperature was 320 $^oC$ and the other deposition parameters are shown in Table 1.

Table 1: Deposition parameters of the $SiO_xN_y$ films deposited by PECVD

| **Material** | **$SiH_4$ Flow** (sccm) | **$N_2O$ Flow** (sccm) | **Pressure** (mTorr) | **r.f. Power** (W) | **Temperature** (°C) |
|---|---|---|---|---|---|
| $SiO_xN_y$ | 15 | 37.5 | 34 | 200 | 320 |

The structures were characterized by optical microscopy to determine the etch rate in the different stages of the tips formation and to investigate the tips morphology changes during the formation process. This is also essential to ascertain the total development time of the tips versus the geometrical dimensions in the initial mask.

## Results and discussion

During the corrosion process to form the tips, we identify three distinct stages, which, due to the different exposed crystallographic planes, are characterized by different tip shapes and etch rates. In the first stage (see Fig.2), the under-etch that occurs in the region among four neighbors square holes in the masking material ($SiO_xN_y$), makes that the walls of the produced cavities move laterally, under the $SiO_xN_y$ film. These walls correspond to (100) planes and, since they are vertical, collapse abruptly when the neighbor cavities meet each other. The result is the formation of an isolated truncated pyramid with a relatively simple geometry since all of its faces correspond to (111) planes.

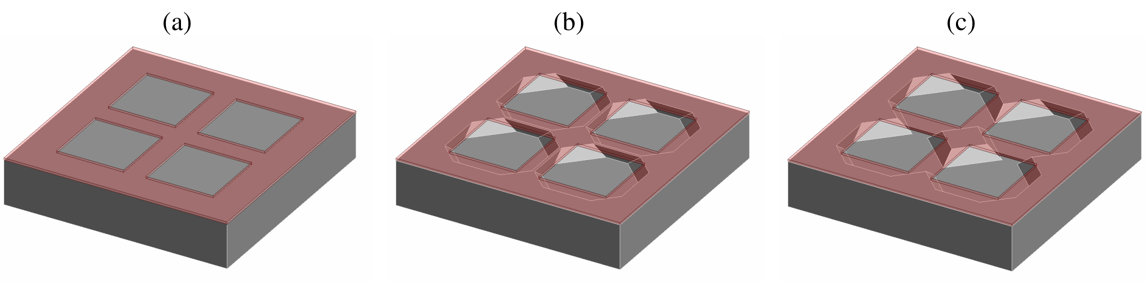


Fig.2. First stage of tips formation: (a) square holes in the masking material before the Si etching in KOH. (b) Middle of the first stage, before the (100) walls collapse. (c) Formation of the isolated truncated pyramid marking the end of the first stage.

The second and third stages are related to the corrosion of the isolated truncated pyramids in Fig.2c and are much more complex due to the appearing and subsequent disappearing of cristallographic planes with high Miller indexes. The 2$^{nd}$ stage is characterized by a rapid corrosion of the edges where the (111) sides of the truncated pyramid intersect (see Fig.3). The characteristic geometry of the resulting structure is normally attributed to the appearance of (311) planes that start to appears at the upper vertices of the truncated pyramids. Note that the 2$^{nd}$ stage ends when the <111> planes meet and the top of the structure transforms into a regular octagon (see Fig.3c).

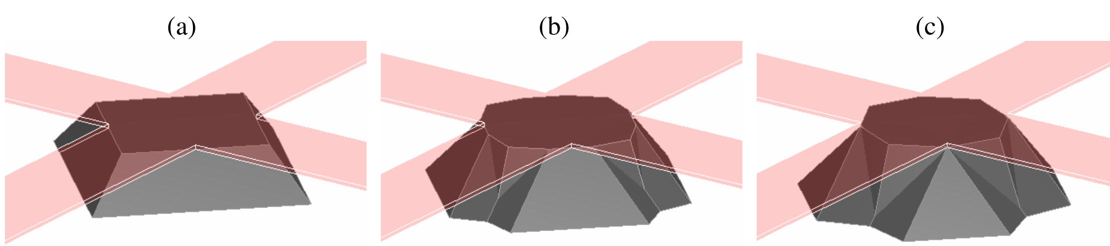


Fig.3. Second stage of tips formation. (a) Start, (b) evolution and (c) end, when a regular octagon on top of the structure is formed.

The 3rd stage is when the sharpening of the structure takes place until the complete formation of the microtip (see Fig.4). The development is completed when it happens the point of the tip unglues completely from the oxynitride film.

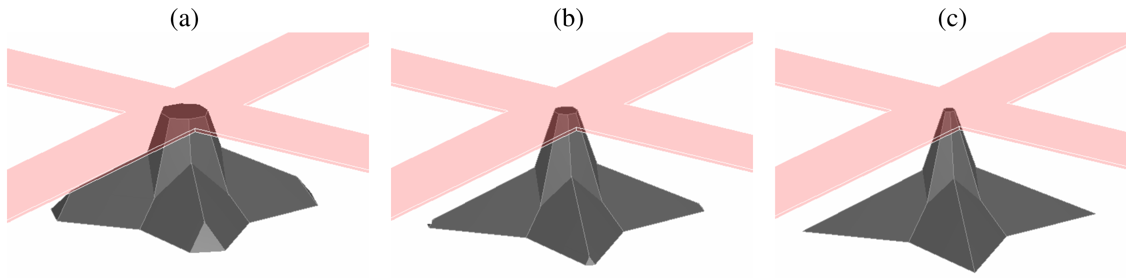


Fig. 4. Third stage of tips formation when the sharpening of the structure occurs until the complete formation of the microtip. (a) and (b) evolution. (c) End of the stage.

As we can see, all the stages are characterized by the corrosion of different crystalline planes families, which leads to different etching rates for each stage. A top view of the microtips in the 1st and 2nd stages and 3D image for the tips after the 3rd stage are shown in Fig.5, where we also indicate the etching rate of each stage, obtained from the lateral displacement of the planes under the $SiO_xN_y$ film. Also, the apex of the microtips have a diameter smaller that 1 µm.

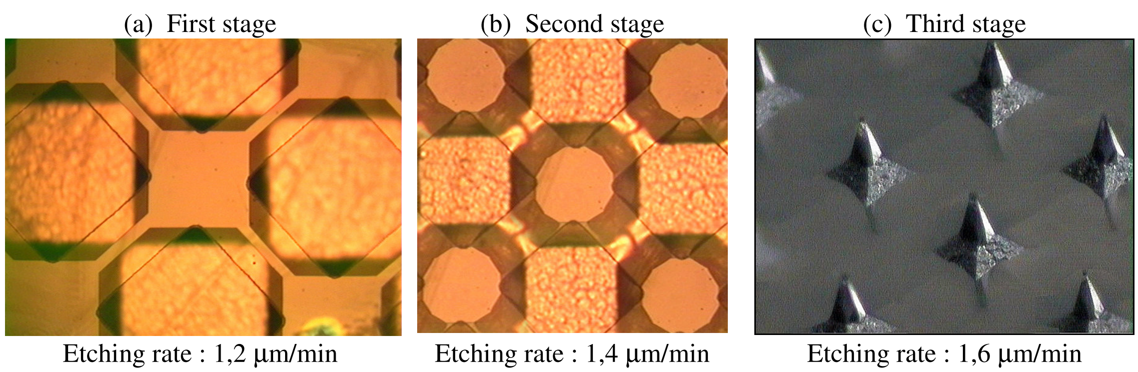


Fig.5. Top view of the microtips in the 1st (a) and 2nd (b) stages of formation. In (c) a 3D image of the tips after the 3rd stage. Here the $SiO_xN_y$ grid was removed to better appreciate the tips geometry.

The structures that were manufactured are matrixes with different number of microtips originated from matrixes of square holes with sides of 100, 200, 300 and 400 µm and separated by a constant distance of 50 µm. After de Si corrosion this separation lead to 50 µm width oxynitride lines that stay self-sustained and form an $SiO_xN_y$ grid that will support the Cr electrode. Also, is the width of these oxynitride lines that defines the final microtip's size. So, in this work all the microtips are approximately 52 µm height. In Fig.6 we show the $SiO_xN_y$ grid over a matrix of 8 microtips formed from square holes of 400x400 µm. As we can see, the grid exhibits excellent structural integrity and flatness, even for a self-sustained length in the order of a millimeter.

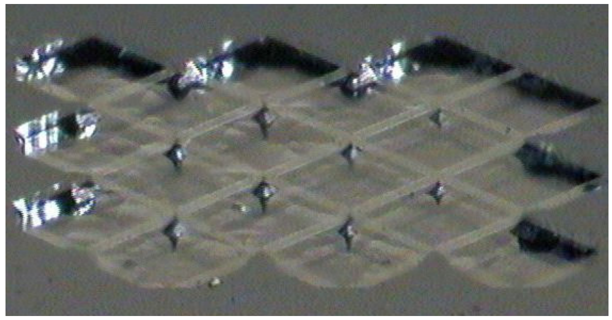

Fig. 6. Matrix of 8 microtips (formed from square holes of 400x400 $\mu m^2$) with the self-sustained $SiO_xN_y$ grid.

The most critical point of the process is to determine the moment to interrupt the corrosion, when the tip is already formed and it detaches itself from the $SiO_xN_y$ grid. In fact, at this point the top of the tips becomes exposed and the corrosion continues at very high speed, making the tips collapse and quickly disappear. On the other hand, it is well known that is difficult to attain a fine control of Si wet etching in KOH. So, an alternative is to utilize a slower corrosion method to finalize the 3rd stage. Following this approach we utilize, with satisfactory results, a dry etching in $SF_6$ plasma for the final sharpening of the tips.

Since they were focused on the fabrication process, the previous figures show the tips without the Cr electrodes to better observe the tips geometry and the self sustained $SiO_xN_y$ grid. However, in this method the metallic film for the electrodes can be deposited before the Si corrosion to form de tips (see Fig.1d). This is possible due to Chromium resistance to KOH solutions. In Fig.7 we show a matrix of 72 microtips with the self-aligned integrated electrodes.

(a) (b)

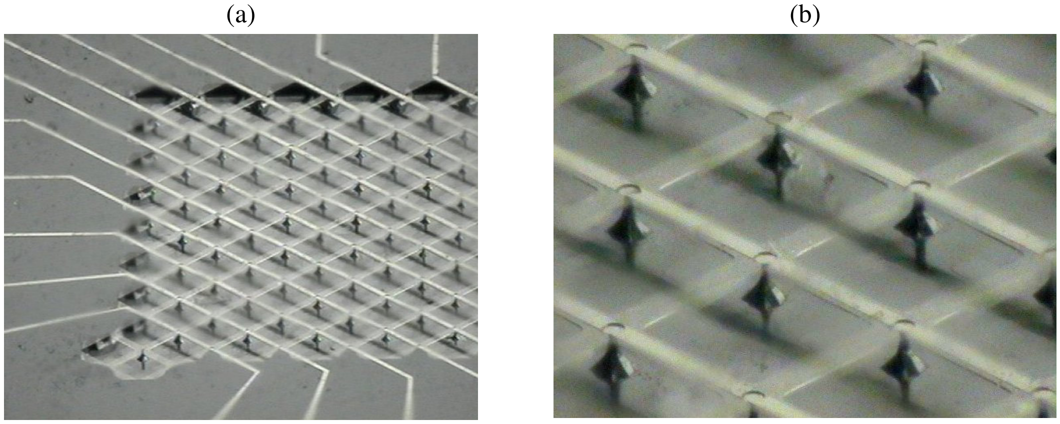

Fig.7. Final aspect of the Si microtips with the self-aligned integrated electrodes. (a) Matrix of 72 tips formed from square holes of 200x200 $\mu m^2$. (b) Detail of the same structure.

As we can see, the structural integrity and flatness of the $SiO_xN_y$ grid allows to produce self-sustained Cr electrodes with lengths in the order of a few millimeters. In fact, in Fig.7a the square holes in the $SiO_xN_y$ films have dimensions of 200x200 $\mu m^2$ which lead to self-sustained Cr lines with a maximum length of up to 2,8 mm and with no structural damages. Besides this, in Fig.7b we can see the self-alignment of the electrodes and a small circular hole with 20 μm of diameter exactly over the tips apex.

This circle corresponds to a region of the $SiO_xN_y$ grid that must be removed to allow the electric current flow between the tips and the Cr electrode.

## Conclusions

Was proposed a very simple method, based on anisotropic corrosion of the silicon substrate in KOH solutions, to fabricate silicon microtips with self-aligned integrated electrodes. The method takes advantage of the under-etch observed when this anisotropic Si etching is carried out trough square holes in the mask oriented $45^o$ respect to the [110] direction in the (100) Si wafers. Also, since we utilize chromium, the metallic film for the electrodes can be deposited before the Si corrosion to form de tips, making the overall process even simpler.

On the other hand, the method requires a low mechanical stress material, with high resistance to KOH corrosion and that preserves its mechanical stability and flatness after the Si tips formation. So, the result reported here depends critically on the superior chemical resistance, mechanical strength and electrical properties of our PECVD $SiO_xN_y$.

Were fabricated matrixes with different number of Si microtips with 52 μm height and with a diameter bellow 1 μm at the apex. The results demonstrate that the structural integrity and flatness of the $SiO_xN_y$ grid allow us to produce self-sustained Cr electrodes with length of up to few millimeters and with no structural damages.

Finally, despite the good results obtained some experimental and technological details must be better studied. For example, is necessary to study the minimum attainable controlled distance between the Cr electrode and the tips apex, which requires further structural and morphological characterization. Is also necessary to make the electrical characterization of the structures in order to identify the conduction mechanism and the occurrence of the electron field emission phenomena. Both studies are been made at the moment.

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