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# A nanotechnology application for low energy neutral atom detection with high angular resolution for the BepiColombo mission to Mercury.

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Thanks to the great progress of micro and nanofabrication techniques, only in recent years it has been possible to propose a space flying instrument able of remote-sensing the surface released neutral particles with a direct technique. This instrument, which will be installed in the BepiColombo/MPO spacecraft to Mercury, is the neutral sensor ELENA (Emitted Low-Energy Neutral Atoms), a time-of-flight (TOF) detector, based on the state-of-the art of ultra-sonic oscillating shutters, and Micro-Channel Plate (MCP) detection. The shuttering system digitizes space and time when tagging the incoming particles without affecting their trajectory and energy. The ELENA shuttering element consists of two self-standing silicon nitride ($Si_3N_4$) membranes, one facing the other, patterned with arrays of 200 nm wide nanoslits, organized on a square lattice with 4 μm pitch over a 3 x 3 $mm^2$ area whereas in the final version it will perform a pitch of 1.4 μm, on a 10 x 10 $mm^2$ area. A capacitive control system is implemented to assure the alignment of the two membranes. The characterization of the shuttering capability has been obtained with a $He^+$ beam at 1 keV. The same fabrication process has been also used to realize a large area mesh filters, in order to reflect unwanted IR radiation to minimize the instrument heat load.

## 1 Introduction

Mercury is a poorly known planet as ground-based observations, even if provide some interesting results, are particularly difficult due to the planet's proximity to the Sun. Nevertheless, it is very interesting for its extreme environmental conditions. The major scientific topics to be addressed are the Mercury's exosphere, its interaction with the solar wind and its origin respect to the surface of the planet: those information can provide important clues about planetary evolution [1]. The ion-sputtering process generated by the solar wind impacting on the surface is particularly intriguing since the involved energies induce escape from the planet of mainly neutral atoms at low energy. The idea of remote-sensing in space the surface released neutral particles, in order to map the emission from the planet, has been proposed for the first time for the BepiColombo/MPO spacecraft to Mercury because of the relevant implication expected on planetary evolution models [2] and, on the other side, of the great progress that micro and nanofabrication techniques have achieved in recent years making this observation possible. When fluxes of neutral atoms at very low energy (down to below 100 eV) have to be detected, keeping at the same time a fine angular resolution, a "direct" technique is needed (that is, that not effects neither the particles trajectory nor their energy). Actually, no inflight instrument has ever been capable to successfully measure low energy neutral atoms using direct detection technique. For this reason a new kind of low energetic neutral atoms instrument, the neutral sensor ELENA (Emitted Low-Energy Neutral Atoms) for the ESA cornerstone BepiColombo mission to Mercury (in the SERENA instrument package [3]) has been proposed [4].

## 2 The ELENA detector

ELENA is a Time-of-Flight (TOF) sensor, based on state-of-the art ultra-sonic oscillating shutters, mechanical gratings and Micro-Channel Plate detectors (MCP). The shuttering system digitize space and time when tagging the incoming particles without introducing detector elements, which may affect the particle's trajectory or the energy: this is particularly important in this case, in which neutrals of energies of a few tens of eVs must be detected. While ion are suppressed in the instrument neck, the neutral particles, ENA, that impinge on the detector entrance, are allowed to enter only with a definite timing: they are then flown in a TOF chamber and are finally detected by a 2-dimensional array based on MCPs with discrete anodes sets. The angular resolution in the direction parallel to the satellite motion is due to the shuttering nanoslits geometry (as described below) while the discrete anodes sets provides the resolution in the perpendicular directions. At the entrance of the instrument, an infrared mesh filter will reflects unwanted IR radiation to minimize the instrument heat load. The ELENA sensor concept is showed in figure 1 and the instrument characteristics are summarized in table 1 [5].

## 2 The ELENA shutter

The ELENA shuttering element consists of two self-standing silicon nitride ($Si_3N_4$) membranes one facing the other (Fig. 2 a)). Silicon nitride has been chosen for its excellent physical proprieties: high Young's modulus, high yield strength, excellent wear resistance and low thermal expansion and conductivity [6]. All these properties, together with the possibility of patterning it, have made silicon nitride one of the most used materials in MEMS applications (Micro electromechanical systems: AFM tips, actuators, sensors, etc.).Those membranes are patterned with arrays of long and narrow nanoslits 200 nm wide and 2.4 μm long each on a square lattice with 4 μm pitch (final version 1.4 μm pitch on the direction normal to the nanoslits) on a 3 x 3 $mm^2$ area (10 x 10 $mm^2$ area for the final device). About $10^5/mm^2$ nanoslits are therefore realized. The motion is obtained by tightly mounting a low-voltage piezo-electric element (PICMA quality by Physik Instrumente), capable to drive the moveable grating of about 1μm up to 100kHz. During the oscillating phase, the neutrals pass-through occurs only when the slits are aligned, thus determining the START time of the TOF analyzer. A patterned capacitive encoder, embedded on the membrane chips (fig. 2), has been realized to control the frequency and the shutter phase, while ensuring the alignment of the two grids.

The fabrication process performed at the Institute of Photonics and Nanotechnology of CNR (Rome) is based on electron beam lithography (EBL), dry reactive ion etching and KOH anisotropic etching. A scheme of the fabrication process is showed in fig. 3. Starting with a 3 inch silicon wafer <100> oriented and covered on both sides with a 1 μm thick low stress silicon nitride layer (commercially available. Deposited by means of a Low pressure chemical vapour deposition), a 30 nm thin chromium layer is deposited with an e-gun evaporation system. An electron beam lithography system, equipped with a field emission gun with electrons accelerated at high voltage (100 kV), is then used to expose the nanoslits pattern together with alignment markers, on a PMMA (PolymethylMethacrylate, positive tone electronic resist) layer 250 nm thick. The EBPG 5HR used for this patterning has the capability of writing over large areas keeping at the same time the correct pitch between each nanoslit because pitch errors could spoil completely the performances of the TOF detector. To avoid this, before to start the e-beam exposure, we checked that the positioning error due to temperature drifts was small enough. This could be achieved by monitoring the position accuracy of the stage by localizing at time intervals of T=15 min a selected marker on the substrate holder. The exposure starts only if the position changes due to temperature drifts in the x direction (the direction normal to the nanoslit) is lower than 10 nm within the time interval T. Another issue to be addressed is the nanoslits width uniformity. Even if it is important, as distortion in width uniformity affects the time resolution of the instrument and hence its performances (wider slits takes more time to be completely closed than narrower slits), it is not as crucial as the pitch errors. Nevertheless, the position accuracy achieved before starting the exposure and the stability of our machine makes the slit width on the whole pattern exposed very reproducible and compatible with the desired performances of the instrument. The pattern is then transferred onto the underneath 30 nm chromium layer by means of a chemical wet etching, suitably controlled in temperature and time in order to achieve the desired resolution (fig. 3a)). This chromium mask is now used to etch by using a RIE step the 1 μm thick silicon nitride layer, without loosing resolution, by means of an anisotropic fluorine based reactive ion etching (fig. 3b)). A double side mask-aligner is used to define large windows on the back side of the wafer aligned with the front nanoslits patterning: lift off of a 30 nm thin chromium layer and a fluorine based reactive ion etching are used to transfer those openings onto the silicon nitride back layer. A wet 23% KOH (Potassium hydroxide) solution at 80°C is used to remove most of the silicon wafer leaving only a 50 μm thick silicon layer (fig. 3c)). This solution etches the <100> planes leaving unaltered the <111> planes (54.74° respect to the wafer surface, <100> oriented). The front side of the wafer is protected during the long wet etching by means of a suitable sample holder. An other EBL step, using a PMMA layer followed by Ti/Au deposition and lift off is performed to obtain electric encoders aligned with the nanoslits in order to control the alignment between the two elements of the shutter (fig. 3d)). The sequence of the process steps has been chosen to avoid the contact of the narrow Ti/Au features with the wet KOH solution that could unstick them from the wafer surface (as Ti can be etched by KOH). At end, an extra wet etching process is then used to remove the unwanted silicon layer and to release the patterned membrane freely standing (fig. 3e)).

A similar fabrication process has been also used to fabricate the infrared mesh filter. In this case, the pattern consists of a square lattice of 1x1 $\mu m^2$ holes with a pitch of 2 μm in both directions covering a 10 x 40 $mm^2$ area: the silicon nitride membrane is covered by a metal layer to reflect the incoming radiation.

The two self-standing silicon nitride membranes of the ELENA shutter have been assembled and sub-micron aligned one respect to the other by means of optical techniques at ISC-CNR and then tested at the IFSI-INAF ion beam laboratory in Rome. The aim of the test was to demonstrate experimentally the shuttering capability of the system. For this purpose, instead of a neutral beam, a $He^+$ ion beam generated by a Penning discharge type ion source has been accelerated at 1 keV in a vacuum chamber. As in the case of the final instrument, also in this case the particles have been detected by means of a micro channel plate. After the characterization of the beam, the ELENA shutter has been mounted in the vacuum chamber and aligned with the ion beam itself. The two membranes that constitute the ELENA shutter are moved one respect to the other by applying a sinusoidal 20 Hz, 48V voltage to the piezo motor. As shown in fig. 4, the shutter was able to allow the particles to enter only when the two membranes were aligned, confirming the excellent quality of the fabrication process.

## 3 Conclusions

The capability of patterning different materials at the sub micrometric scale allows the design and realization of new devices/instruments with unprecedented performances. A time-of-flight (TOF) instrument, based on the state-of-the art of nano patterned piezo-driven ultra-sonic shutters, and a Micro-Channel Plate (MCP) array sensor has been proposed for neutral particles detection with a direct technique. The first experimental results show the good functionality of this system via the capability of the shutter to open and close an ion beam flux revealed by a MCP stop detector.

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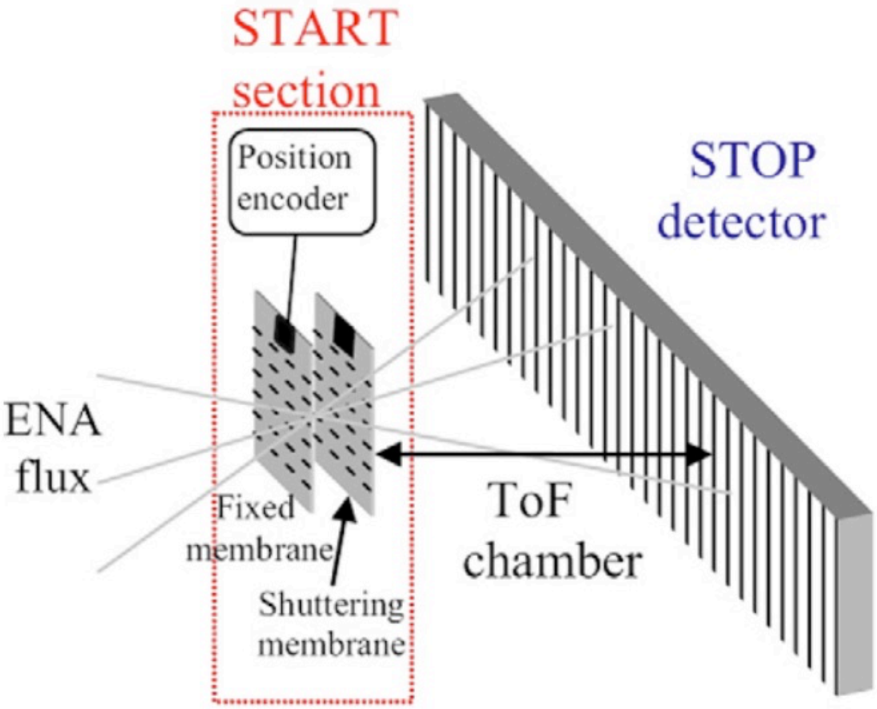

Figure 1. Schematic view of the working principle of the ELENA detector: the neutral particles impinging on the detector are allowed to enter only with a definite timing by the starting element (the so called shutter), they then flow in the TOF chamber and are detected by a micro channel plate.

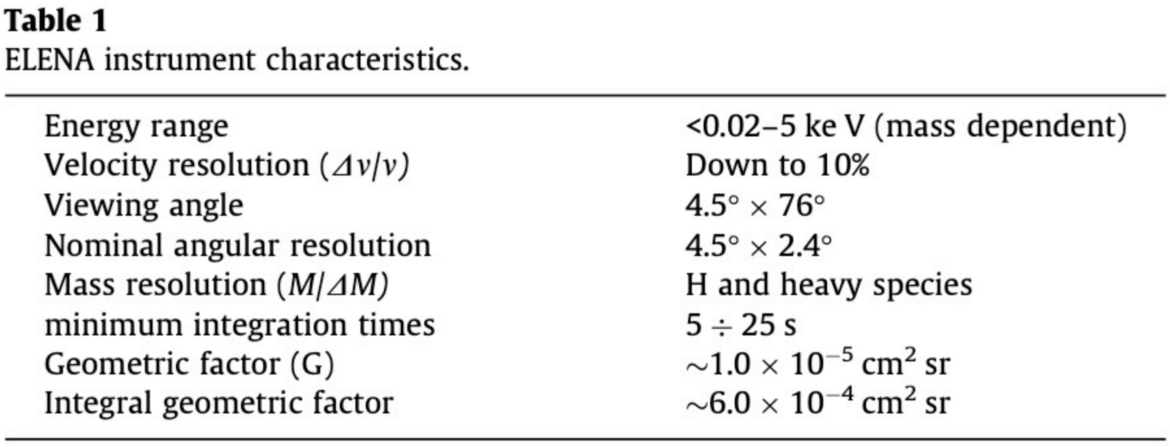

**Table 1**
ELENA instrument characteristics.

| | |
|---|---|
| Energy range | <0.02–5 ke V (mass dependent) |
| Velocity resolution ($\Delta v/v$) | Down to 10% |
| Viewing angle | $4.5^\circ \times 76^\circ$ |
| Nominal angular resolution | $4.5^\circ \times 2.4^\circ$ |
| Mass resolution ($M/\Delta M$) | H and heavy species |
| minimum integration times | $5 \div 25$ s |
| Geometric factor (G) | $\sim 1.0 \times 10^{-5}$ cm$^2$ sr |
| Integral geometric factor | $\sim 6.0 \times 10^{-4}$ cm$^2$ sr |

Table 1. ELENA instrument characteristics.

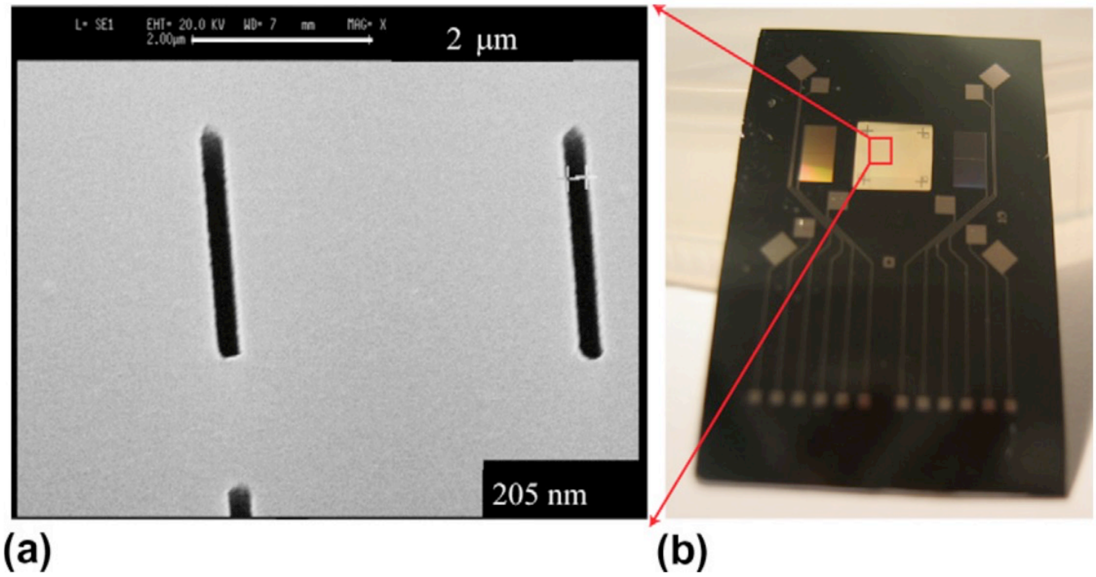

Figure 2. a) Scanning electron micrographs of the ELENA shuttering elements. b) One of the two self standing patterned membrane of the shutter: in the chip together with the membrane, capacitive encoders are fabricated to control alignments.

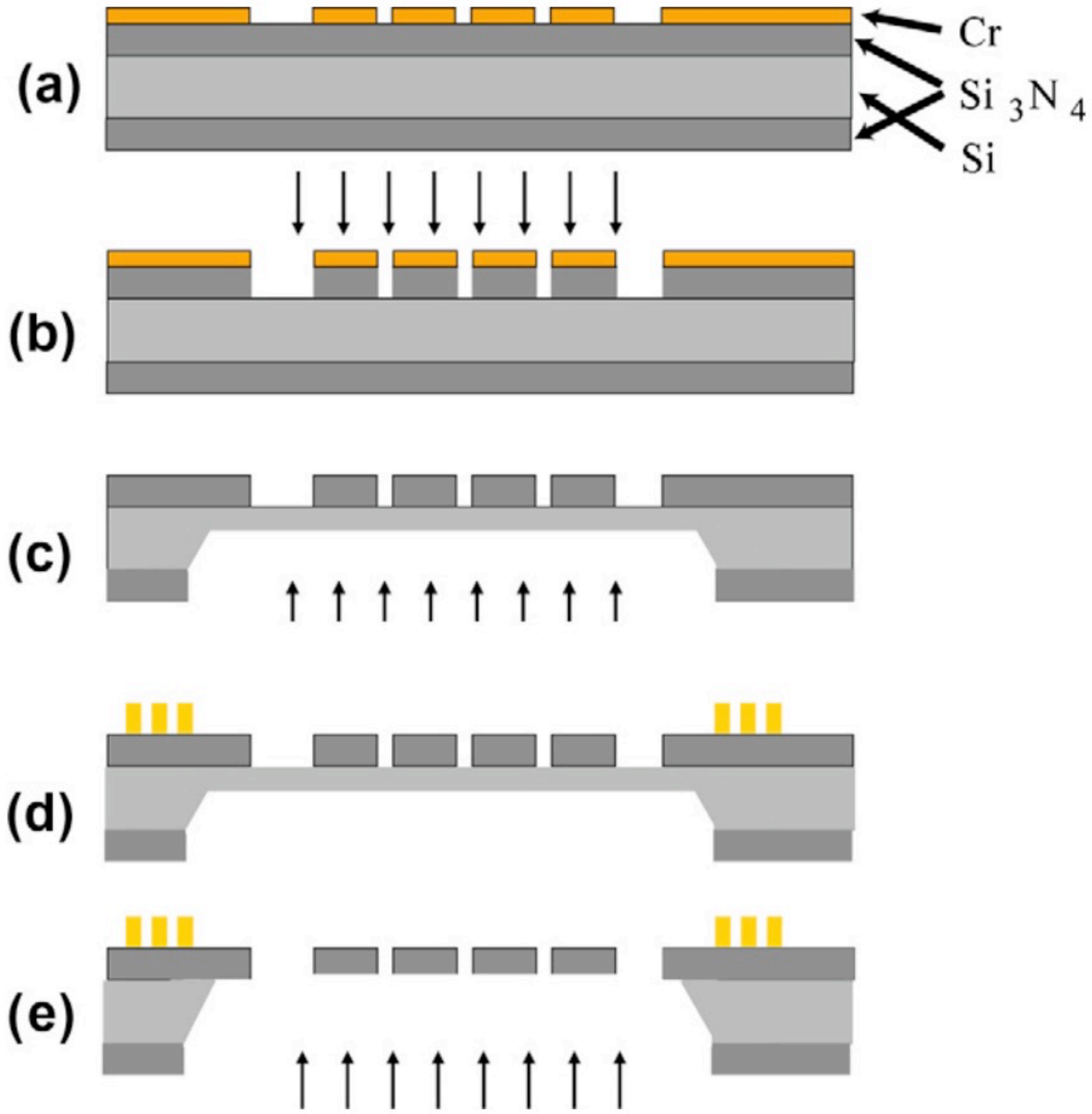

Figure 3. Schematic view of the fabrication process as described in the text. The Process starts with a commercial 3 inch silicon wafer <100> oriented and covered on both sides with a 1 μm thick low stress silicon nitride layer as described in the text.

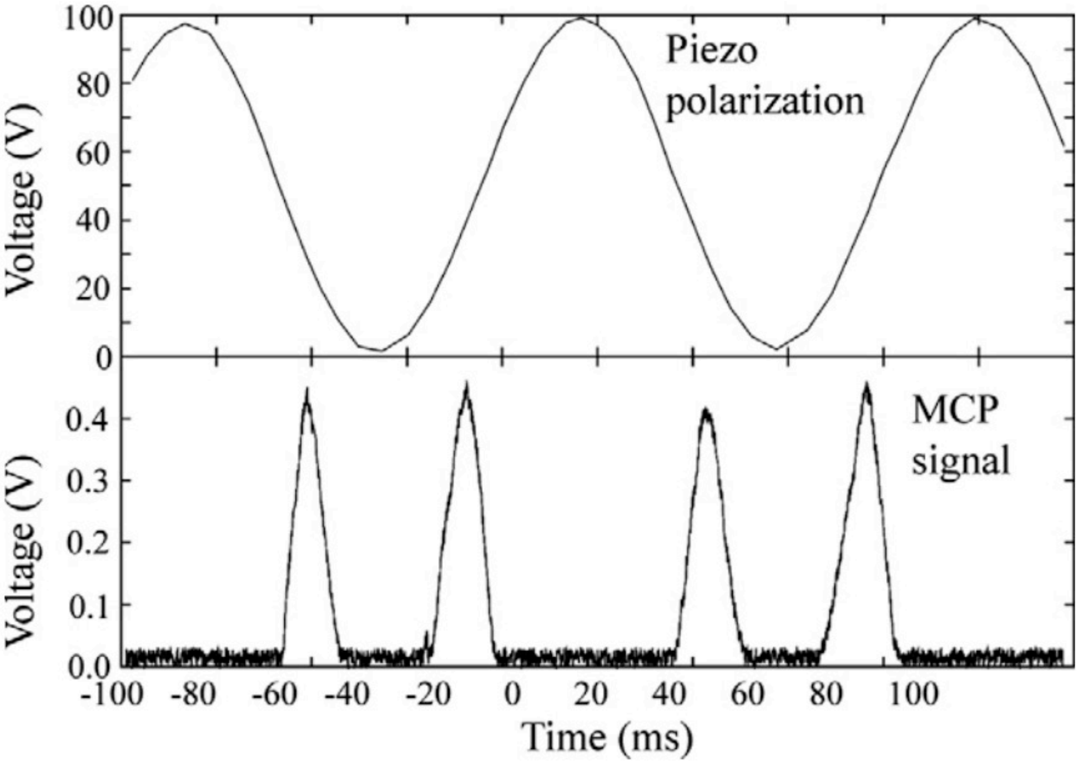

Figure 4. Characterization of ELENA shuttering capability obtained at the IFSI-INAF ion beam laboratory with a $He^+$ beam at 1 keV. The ion beam is allowed to reach the detector only when the two membranes are aligned.