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DELIVERABLE 4.1

10 mm TO 1 mm AND 1 mm TO 10 µm NODES MECHANICS CALCULATOR ASSESSED

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MEMO – Mechanics with molecules
MEMO has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 766864.

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1. INTRODUCTION: THE MEMO ROADMAP

The MEMO Roadmap for miniaturize a mechanical calculator defines five technology Nodes (see table below):

Node 1: between 10 mm and 1 mm
Node 2: between 1 mm and 10 μm
Node 3: between 10 μm and 100 nm
Node 4: between 100 nm and 10 nm
Node 5: the molecular scale

Those nodes were essentially determined following the miniaturization trends of gears with their associated technologies and processes. ***Node 1*** is normally accessible by machine tools, by 3D printers and now also by laser cutting. ***Node 2*** is accessible by optical lithography using physical static masks or scanning optical lithography and the sacrificial layer technique [1]. ***Node 3*** is normally needs e-beam lithography and, at small dimension (typically below 100 nm), the drawback of the backscattered electrons [2]. Therefore, MEMO decided to rely on the new He+ HIM lithography technique which can be seen as an improved version of the Field Ion Beam technique usually based on Ga+ ions [3]. ***Node 4*** is the most challenging one, because it is essentially at the transition between the macromolecules size of the lithography resists used in Node 2 and 3 and the single molecule gear mechanics. It is also at the scale of proteins gears and motors [4]. ***Node 5*** deals with the scale of single molecule machinery [5]. As indicated in the table below, there are no net borders between each Node. For example, laser cutting can bring the miniature gears of Node 1 to approach 0.5 mm, a size that optical lithography can reach. For example, very long e-beam time can pattern 100 mm gears which can transfer rotation motion in a train of gears from 100 mm to 100 nm by having the same tooth size all the way down.

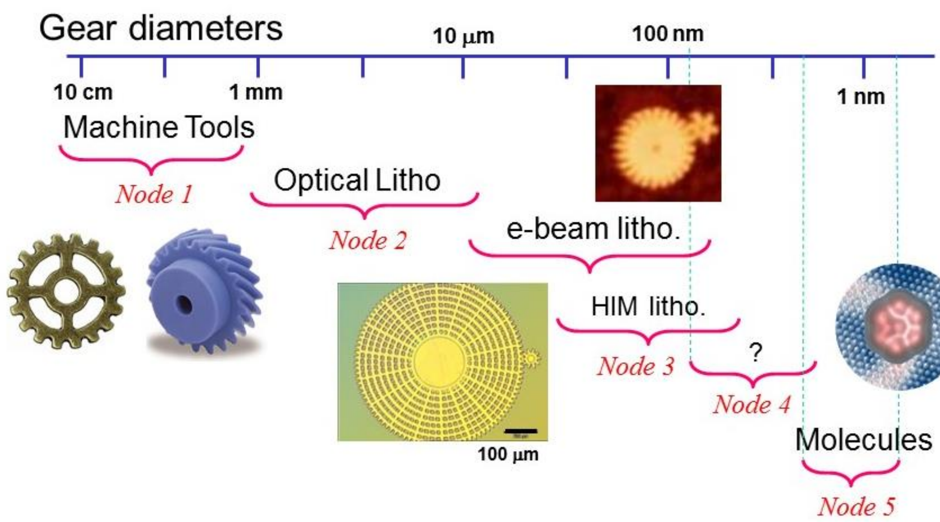

Table 1: *The MEMO Roadmap with its five Nodes based on mechanical gears miniaturization*

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In a mechanical calculator, there are however not only gears. There are other essential mechanical devices like springs, sliders, beams, ratchets, rotation axles and also holders and screws to maintain all those mechanical pieces in place. Friction between those different mechanical parts also plays an important role at any scale. Therefore, MEMO decided to revisit Node 1 and 2 not only with the molecular scale in mind, but because of all the other mechanical pieces which have also to be miniaturized and whose designs may change from scale to scale. Furthermore, having a gear, a beam, or a ratchet fabricated in a given Node can always be an advantage for the transmission of rotation motion to another scale explored by another Node as soon as the functioning environment for the 2 scales covered by those 2 Nodes is compatible.

Deliverable D4.1 covers Node 1 and Node 2. We will present here the work done by partner P2.1-Toulouse in MEMO Tasks 4.1 and 4.2.

2. THE 10 mm TO 1 mm NODE FOR A MINIATURE MECHANICAL CALCULATOR

The main purpose on this node was to duplicate and then to create a miniature mechanical calculator using at the end gears with 1 mm in diameter. At the beginning, P2.1 Toulouse have analysed the mechanical calculator machinery that have been designed and manufactured far in the past in order to learn what design can be adapted for a scale reduction of the gears and can work using modern manufacturing tools like 3D printing, ultra-precise electro-erosion and laser microfabrication. This historical analysis was performed by visiting science museums in Paris and Dresden and was very much facilitated by interacting with the largest mechanical calculating machine museum in Europe: the n Bonn. One consequence of this interaction was that MEMO had invited the head of the *Arithmeum* to the first MEMO Academy-Industry meeting in Dresden (see WP 5.3).

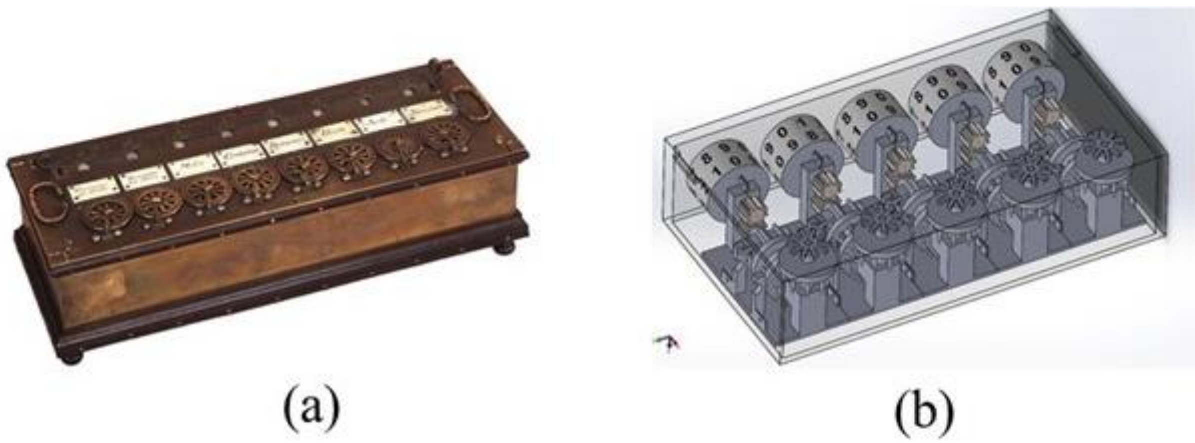

***Figure 1**. (a) The original second generation in metal of the Pascaline (Arithmeum museum) and (b) an example of a 5 stages Pascaline calculating mechanism.*

The oldest mechanical calculator is the Pascaline constructed in 1642 by B. Pascal (Fig. 1a). It is essentially a "gravity" machine whose miniaturization in a planar form is rather delicate since, by reducing the size, there

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will be no more gravity effect. Therefore, the essential carry operation from stage to stage should be performed in another way to allow miniaturization. Furthermore, and considering only one stage of the Pascaline calculator, 5 gears, 3 shafts and 2 different directions of rotation are involved. This results in a lot of mechanical parts that should be miniaturized and assembled: 56 parts for a 5 stages mechanical calculator as presented in Fig.1b. Anticipating also the MEMO roadmap, such a complex mechanical structure would be rather difficult to fabricate, for example, by optical or He+ lithography technology.

Fortunately, and about 100 year later, the German clock maker G. Auch succeeded in fabricating a smaller and planar version of the Pascaline using springs and a mechanical slider instead of the gravity effect to perform the carry operation (Fig. 2a).

(a) (b)

***Figure 2**. The Auch mechanical calculator (Mathematisch-Physikalische Salon, Dresden)*

With the help of the *Arithmeum* museum in Bonn and of the *Mathematisch-Physikalische Salon* in Dresden, P2.1 Toulouse analysed this Auch machine beneficiating from a 3D virtual animations provided by the *Arithmeum*. The Auch mechanical calculator requires 20 parts less than the Pascaline to assemble a 5 stage calculator. Therefore, P2.1-Toulouse decided to start to fabricated a 3D printed model of the Auch calculator to study its functioning in detail and determine how to miniaturize it under the P2.1-Toulouse 3D printing machine. Notice that the Auch design is flatter than the Pascaline one but there are still 3 stages of gears and a big slider for the carry operation as presented in the CAD model of Fig. 3a. Such a long sliding part is an issue for future miniaturization. Besides, the carrying on the Auch machine uses torsion springs instead of the gravity of the Pascaline. Fig. 3b presents the first ever 3D printed version of the Auch mechanical calculator. It was CAD design, 3D printed piece by piece and assembled by P2.1-Toulouse. Only the torsion springs have been made by hand. The gears have a diameter of 4 cm. This model represents the starting point for the Node 1 of the MEMO roadmap (from 10 mm to 1 mm).

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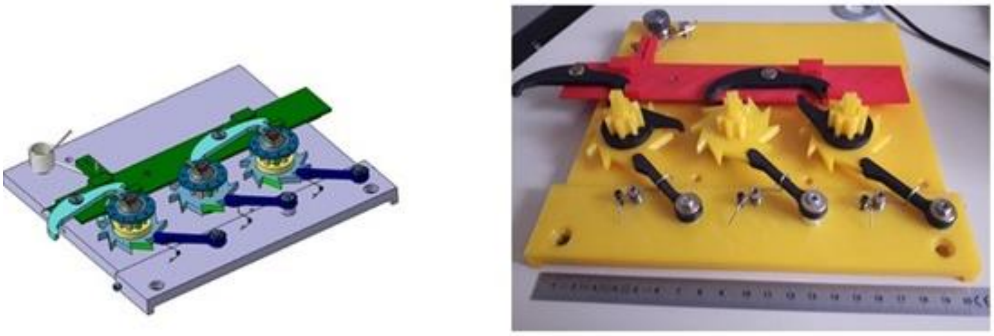
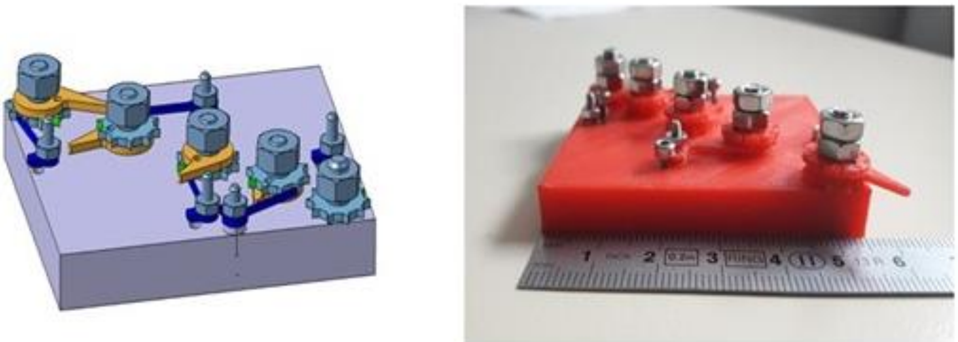


(a) (b)

***Figure 3**: (a) The CAD design and (b) the 3D printed Auch calculator 20 cm long with 40 mm in diameter gears*

After testing the functioning of the 3D printed version of the Auch machine (Fig. 3), P2.1-Toulouse succeeded to reduce the number of its mechanical parts, to flatten its design (to avoid gears stacking) and to substitute the handmade metallic springs by compliant beams (the blue mechanical parts in Fig. 4a). P2.1-Toulouse also succeeded to suppress the original long slider of the Auch machine. The rationale behind the usage of compliance beams was that such beams can be fabricated flat on a surface by lithography technique as compared with the handmade metallic springs of Fig. 3. A few 3D printed versions of the CAD design of Fig. 4a were fabricated taking also into account the miniaturization objective of Node 1. The resulting functioning model is presented in Fig. 4b. The gears have now a diameter of 6 mm. This mechanical calculating machine has now only two active levels per calculating stage, using an alternation of ratchet beam and carry per stage. Only the screw holding each gear on its rotation axle is still very large. This miniature mechanical calculating machine is working perfectly and its number of calculating stages can be increased easily.



(a) (b)

***Figure 4:** (a) The CAD design and (b) the 3D printed P2.1 Toulouse mechanical calculator 55 mm long with 9 mm in diameter gears.*

Let us insist on the fact that in the design of Fig. 4, the original long slider of the Auch machine has been removed in order to use only rotational movement. Another significant improvement is that the springs had been replaced by flexible beams whose material will have to be optimized depending of its length to get the good beam spring constant (blue parts in Fig. 5). In this minimal design, there is only one gear and one pusher for the

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carry (yellow parts in Fig. 5) stacked per stage. The beams holder had also been designed to allow a unidirectional rotation of the calculating gears.

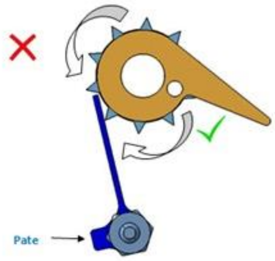

Figure 5*: One calculating stage of the P2.1 Toulouse mechanical calculating machine CAD designed with only 2 active levels. Notice the remaining screw to fix up the ratchet beam to the support.*

Partner P2.1-Toulouse decided to use this design to build a miniature mechanical machine at the full possible capability of modern machine tooling. Fig. 6 presents the metallic pieces which have been fabricated: the miniature beam by laser cutting and the miniature gears by electro-erosion at the limit of this fabrication machine. For this last miniaturization step, metal was preferred to the plastic of the 3D printer because of the robustness of metal mechanical pieces at the millimetre scale. A five-stage mechanical calculator is now in fabrication to be directly implanted on an UHV compatible Omicron sample holder plate. Due to the *Computer Numerical control machine tool* breakdown at P2.1-Toulouse, this final fabrication step requires a complete machine tool fabrication of the sample holder (see an example in Fig. 7) because of the minute axle required for a 2 mm gears. It will normally be fabricated by the end of November 2018 and all those miniature mechanical pieces will be mounted under an optical microscope.

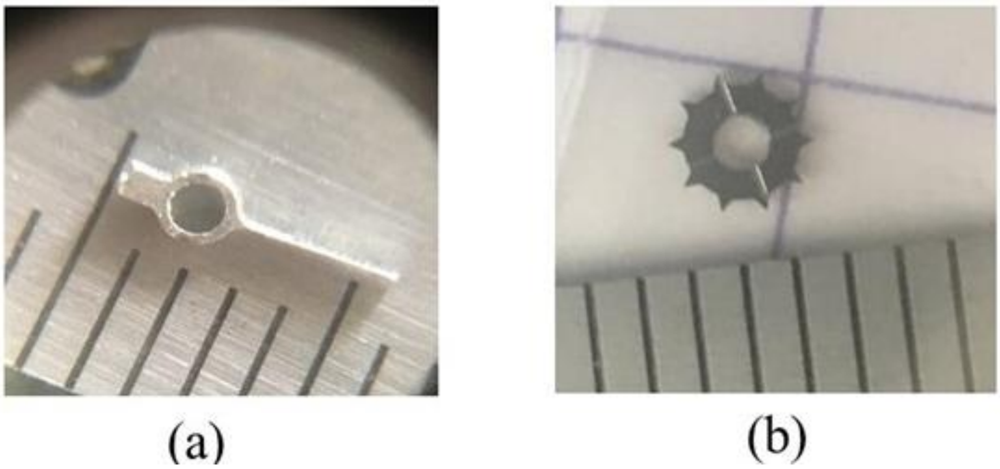

Figure 6*: (a) a 5.6 mm long and 100 μm thick laser manufactured beam fabricated for P2.1 Toulouse by the Micro Tolerie Dallard Company and (b) a 2 mm metallic milli-gear manufactured on the P2.1 Toulouse electro-erosion machine tool requiring a central axle of section lower than 1 mm which must be attached to the surface.*

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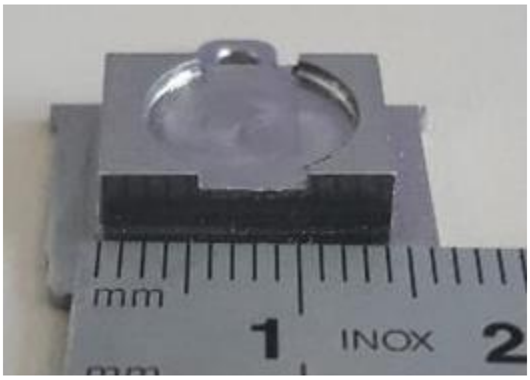

Figure 7*: One example of an UHV compatible Omicron sample plate 14 mm in lateral size to be machined for the assembly of a 5 stage miniature mechanical calculator using the Fig. 6 mechanical pieces.*

After having completed Node 1 for Task 4.1, P2.1 Toulouse decided at the end of the first MEMO period to push forward the mechanical design to reach a complete planarization of a mechanical calculator. This is in preparation of the optical and He+ lithography fabrication of mechanical calculators for Nodes 2 and 3. For this purpose, CAD design had permitted to open a new way of designing calculating stages by implanting the carry tooth directly on the gear. With this design, one can now avoid the stacking of the pusher on top of a calculating gear. Has presented in Fig. 8, the compliant ratchet part must have now a very specific design to allow rotation of the calculating gear in only one direction and perform the carry to the benefit of the next gear. This design was developed at the end of the period for Node 2 and Node 3. It will be tested during the next MEMO period.

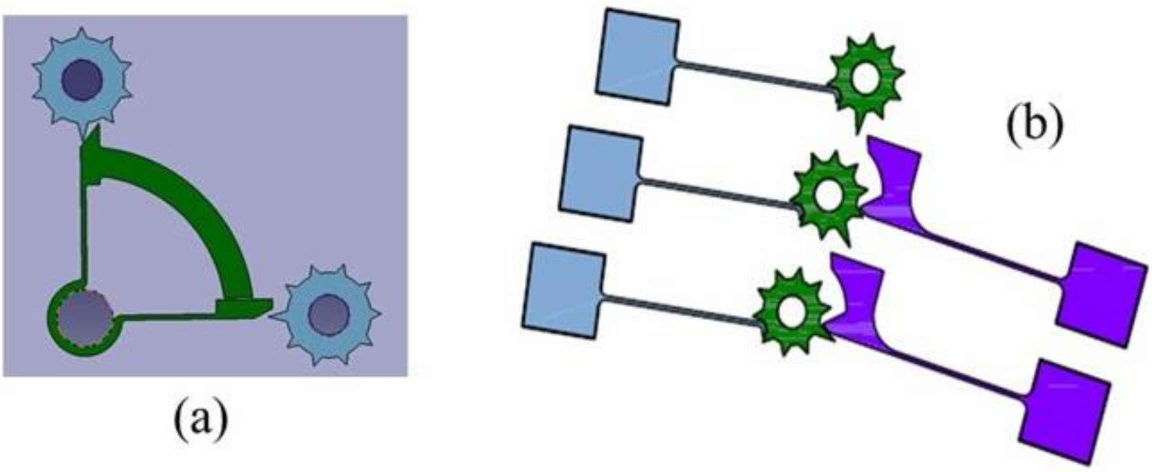

Figure 8: *New beam designs to reduce the number of active layers per calculating stage. (a) A rather modern totally deformable ratchet (in green) between two calculating stages inspired for a new clock industry design and (b) a more standard compliant ratchet like design but with a very asymmetric end per ratchet (dark blue) for assembling a three calculating stage with two carries.*

Prototypes of these two new designs will be fabricated using the P2.1-Toulouse 3D printer to certify their functioning. The CAD design of Fig. 8b was also transferred for fabrication and if necessary improvements to the watch maker TagHauer during its participation to the MEMO Academy-Industry meeting in August 2018 in Dresden (see WP5.3).

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3. THE 1 mm TO 10 μm NODE MECHANISMS FOR A MECHANICAL CALCULATOR

3.1. INTRODUCTION

The results of MEMO Task 4.1 presented above demonstrate that a mechanical calculator can be reduced in size, miniaturizing the diameter of its calculating gears from a few centimetres to a few millimetres. It was also demonstrated that the minimum number of layers per calculating stage can be reduced to one by a very specific beam-ratchet design to ensure the carry transmission and a one-way rotation of the gear at each calculation stage.

Going down in scale from the millimetre to the micron scale, it is requiring to use lithography techniques to micro fabricate the mechanical parts of the calculator: gears, axles of the gears, beam-ratchets, and beam fixers. One has also to pay attention to the fact that below a certain miniaturization scale, it will be difficult to mount all those mechanical parts one after the others using small tweezers or even micro-tweezers. It is therefore necessary to be able to fabricate by lithography all those pieces almost at once and certainly at the same surface level.

For Node 2 (1 mm to 10 μm), P2.1-Toulouse has chosen to use optical microlithography instead of e-beam nanolithography because, for 10 microns scale mechanical devices, e-beam would be too slow and would dose too much the supporting surface by back-scattered electrons. To be compatible with the software of the 3D printed mechanical calculator presented above, P2.1 chosen to use scanning optical lithography. This technique has also the advantage to be more flexible since the mask is stored in the computer and is not a static mask that needs to be physically refabricated at any modification of the mechanical design. P2.1-Toulouse used its DILASE 650 KLOE scanning optical lithography instrument presented in Fig. 9. It is a direct laser writer with an optical beam of 2 μm diameter with two possible working UV wavelength: 375 nm and 405 nm depending on the resist. With this instrument one can select the scanning speed, the focus and the power of the optical insulation.

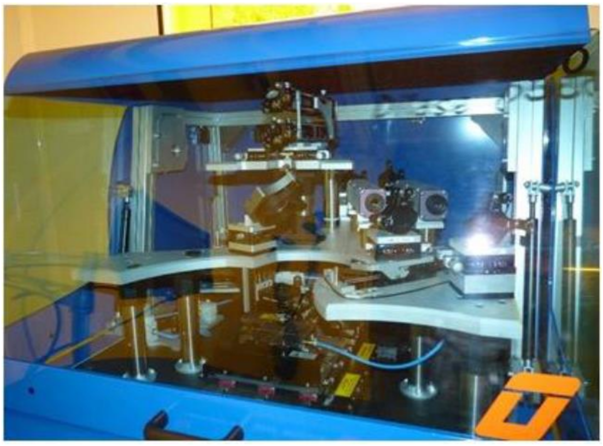

Figure 9: *A photography of the DILASE 650 KLOE instrument used to fabricate micro-gears, micro-beams and anchoring pads.*

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All the microfabrication tests were performed in a cleanroom on the native SiO_2 surface of a 500 µm thick silicon wafer. Then, P2.1-Toulouse transferred this process to a thin graphite surface, contact printed on the SiO2 surface to minimize the friction between the movable mechanical parts and this supporting surface. Those specifically surface graphite/SiO2/Si wafers were prepared by P2.1-Toulouse and also provided to P2.2-Orsay to test He+ nanolithography on the same surfaces.

P2.1-Toulouse used three different types of resists, which were all spin coated on the wafer whose lateral size varied from 1 to 2 cm. Hereafter, V2 is the acceleration (rpb/sec), V the rotation speed (rmp) and T the complete rotation time. To prepare the anchorage of the micro-gear axles, a positive AZ 5214 was used with V2 : 2000, V : 4000, T : 30 s and a 105°C anealing temperature for 1 mn leading to a 1.4 µm resist thikness. For the fabrication of micro-gears themselves, one negative resist was AZnLoF with V2 : 3000, V : 3000, T : 30 s and a 100°C anealing temperature during 1 mn leading to a 6 µm resist thikness. The post-annealing temperature after exposure was 110°C during 1 mn. The other one was the well known SU-8 – 3005 [6] with V2 : 3500, V : 3000, T : 30 s and a 95°C anealing temperature during 3 mn leading to a 8 µm resist thikness. The post-annealing temperature after exposure was here 95°C during 3 mn. Let us insist on the fact that with this P2.1 Toulouse process, it is the remainin resist material itself which consistitutes the micro-gear material. Therefore and after the revelation generally in acetone the remaining part of the resist is also hard baken at 125°C during 3 mm to insure the material cohesion of each micro-gear and of the micro-beam.

3.2. SCANNING OPTICAL MICRO-LITHOGRAPHY FOR THE MICRO-GEARS

As presented in Fig. 10, the computerized mask defines the number of scanlines per insulation field and the red parts of each line, the active insulation segments per scanline. A resulting series of 3 micro-gears on the SiO2 surface after insulation, revelation, rinsing and baking is also presented in Fig. 10.

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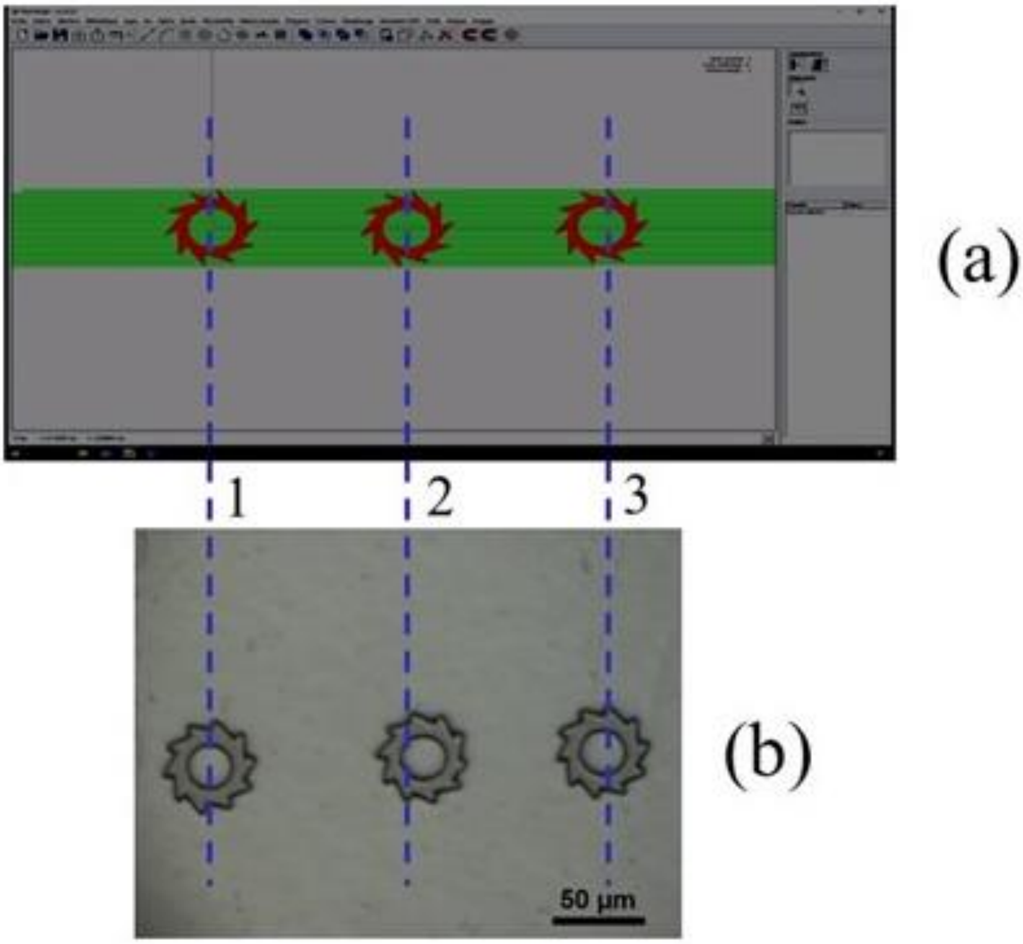

Figure 10: *(a) A photo of the computer screen after the construction of the mask to fabricate 3 micro-gears in series. There are 50 green scanlines 1 mm regularly spaced leading to 50 μm in diameter micro-gears. The red parts of each scanline is the insulation segment of the AZnLoF resist. (a) The final result at the end of the process: three 50 μm in diameter micro-gears (6 μm thick) with 10 asymmetric teeth. Notice the 10 μm shift of the resulting micro-gear 2 due to a software conversion shift which was corrected later (see Fig. 11 below).*

Different size, shape and combination of micro-gears have been obtained starting from the very large 0.9 mm (Fig. 11a) to 30 µm (Fig. 11d). Notice that it was very difficult to rotate or displace them on the SiO_2 surface using for example a glass micropipette as a pusher.

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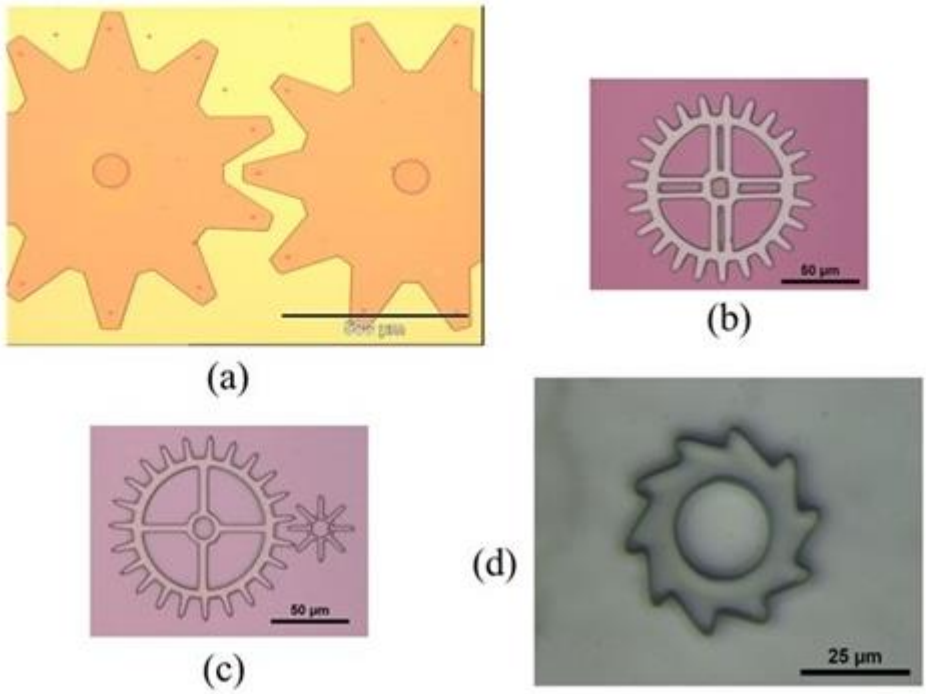

***Figure 11**: Different kinds of micro-gears micro-fabricated on a SiO2 surface using the AZnLoF resist. (a) A very large almost milli-gear with the axle hole not free. (b) A simple micro-gear with 23 teeth and an empty central part and rigidification bars. (C) A train of 2 micro-gears, the second one having a 40 μm diameter. (D) A small 30 μm micro-gear with 10 asymmetric teeth and a large central hole to accommodate an axle.*

3.3. FABRICATION OF MICRO-GEARS WITH THEIR CENTRAL AXLE

An axle of rotation is usually one of the most difficult part to fabricate and this (and any) scale (see for example MEMO D1.1 for the atomic scale) since whatever sequence of fabrication is used (the axle being fabricated before, at the same time or after the gear), either the axle or this gear can be damaged. Furthermore, an axle of rotation must be very robustly anchored to the supporting surface and this is not always possible depending on the material of the supporting surface. During this first year, P2.1-Toulouse had followed two paths: axle fabrication at the same time than the micro-gear or after the micro-gear fabrication.

For a fabrication at the same time and as presented in Fig. 13a, the design was to define a computerized mask where during the laser scanning, the centre of the micro-gear is filled up by its axle. We have tried different axle shapes. The best one to avoid lateral adhesion between the interior of the gear and the axle was found to be a cross as presented in Fig. 13a. The problem with this cross axle is that its height is the same than the thickness of the micro-gears because made of the same resist thickness. Therefore, there is no clipping effect and when the micro-gear is willing to move (rotate), it will easily be dismounted from its axle. Furthermore, if this micro-gear rotates (which is not often the case on SiO_2 but which will be the case on a supported graphite surface (see below)), this cross axle was found to move too.

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Therefore, P2.1-Toulouse explored a second design, first anchoring the axle and then fabricating the micro-gears. For this purpose, it was necessary to select another material than the insulated and annealed resist for those axles. P2.1-Toulouse chosen metallic axles, either Al or Ni pillar normally 10 to 20 μm in diameter and 8 to 10 μm high. A first lithography step was performed using a positive AZ 5214 resist (or AZ 4999), followed by the UV 375 nm insulation, the resit development and the growth-anchoring of the metal pillar by their electrolytic deposition. The resist is then completely washed out in isopropanol for the supporting surface to be ready for the second micro-gear optical lithography step. An example of such a network of micro-axles is presented in Fig. 12.

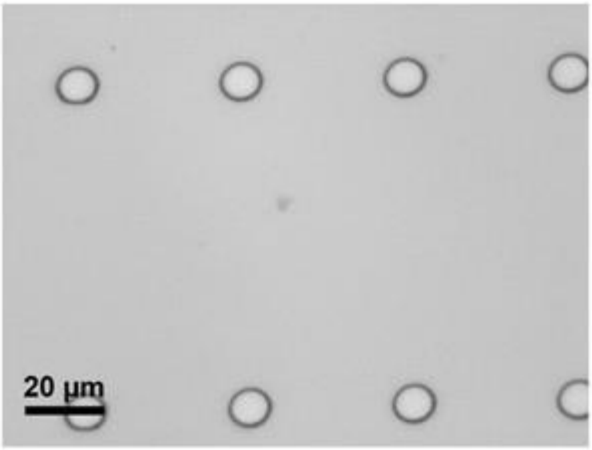

Figure 12: *An example of a series of 8 Al pillar 10 μm in diameter and 10 μm high fabricated and anchored well at the SiO2 surface.*

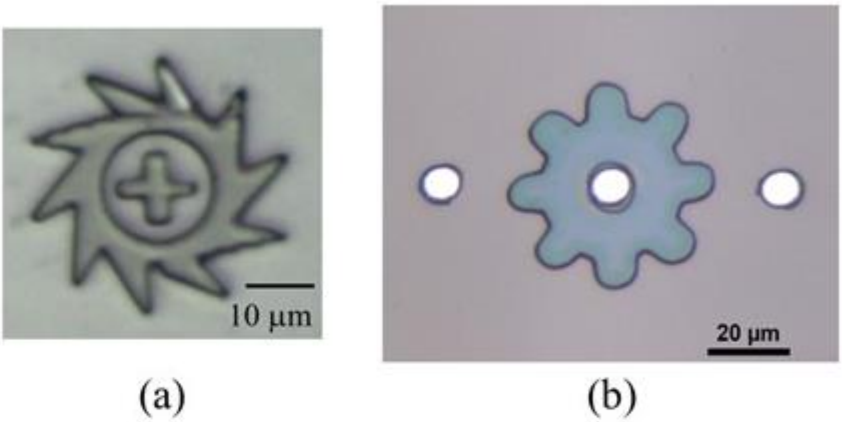

Figure 13: *Two example of micro-gears with their axle. (a) The cross like axle was fabricated at the same time than the micro-gear and in (b) the Al pillar axle was fabricated before in a first optical lithography step and the micro-gear after in a second step and using another resist.*

After the axle fabrication, a new resist can be spin coated to perform the micro-gear insulation also using the optical scanning lithography. The lithography process is here the same that the one described in section 2.2 above including the final baking to ensure the material cohesion of each micro-gear now mounted on its metallic axle. Here the power of this scanning optical lithography technique is used because the re-alignment of the

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center of the micro-gears on the already fabricated micro-pillar is quite simple and very reproducible. This leads to a nice mounting of a micro-gear on its metallic axle as presented in Fig. 13b and this is very reproducible as presented in Fig. 14.

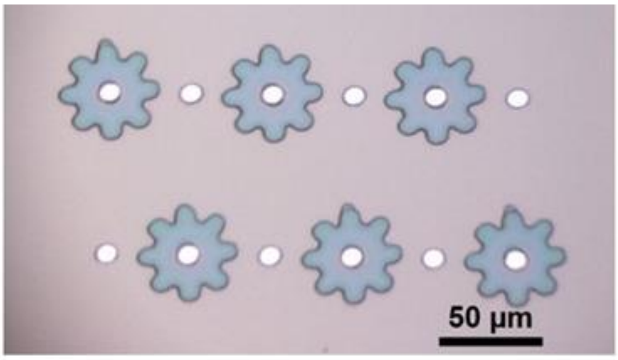

Figure 14: *A network of 12 Al axle with 6 non interdigitated micro-gears showing the precision of this double step process. Such a design was tested in preparation of a 6 stages mechanical calculator where the 6 free Al pillars were supposed to hold the beam for the carry.*

3.4. FABRICATION OF MICRO-BEAM FOR RATCHET AND ANCHORING PADS

As designed in Node 1, the essential part of a mechanical calculator is the beam supposed first to play the role of a ratchet for the calculating gear to rotate only one way and second with the new flat design proposed in Fig.8, to transfer the carry from calculating gear to calculating gear. Those beams must also be anchored to the supporting surface. Notice that the millimetre scale, this anchoring is ensured by screws which is impossible here.

As presented in Fig. 15, P2.1-Toulouse decided at this stage to test the microfabrication of a two-stages mechanical calculator having all the required mechanical pieces: two calculating micro-gears with one gear having a longer tooth to transfer the carry, two axles, two ratchet-like beams with their characteristic asymmetric end and two large anchoring pads to anchor each beam. This design was inspired by the mechanical calculator in millimetre size proposed at the end of Node 1. P2.1 just decided to use for this first test only one raw of ratchets considering that, due to surface friction, the calculating micro-gears would not turn back after a rotation actuated (see below) by a glass micro-pipette.

One important point in the design of Fig. 15 was the thickness of the beams and the lateral size of their anchoring pads. In absence of a precise measurement of beam elasticity and spring constant fabricated with a polymerized and baked SU-8 resist of 8 mm initial thickness, we have tried different lengths,widths, and anchoring shapes to the end pad. After a few trial and error (see section 2.6 below), P2.1 selected a 4 mm width, a 45 mm length and a curved attachment to the anchoring pad (see Fig. 16). This will certainly require more study, particularly at the nanometre scale.

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The end curved shape of each beam was also a subject of large discussion especially after the unique mechanical design proposed in Node 1 Fig. 8. For this first complete design a very simple curvature was adopted assuming that the longitudinal rigidity of each beam will stabilize the ratchet effect.

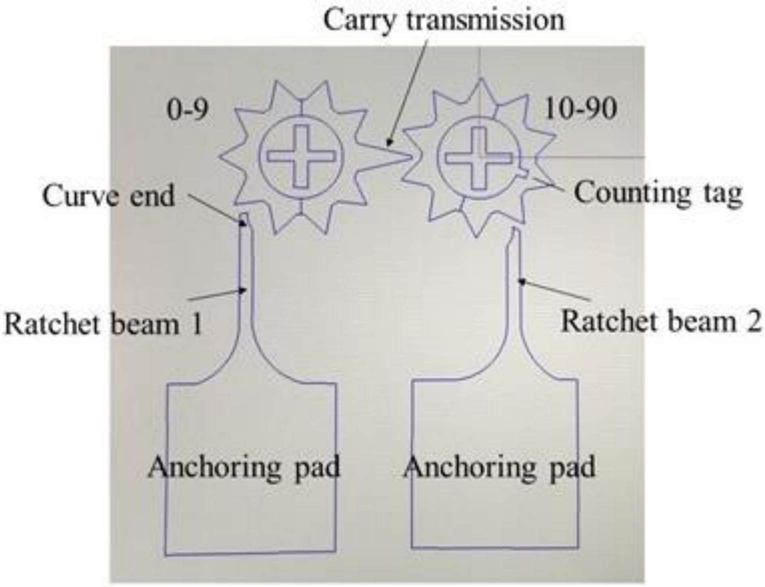

Figure 15: *The complete design for the scanning optical microlithography of a 2 stages mechanical calculator using surface friction to avoid the back rotation of each calculating micro-gear during the carry operation. The gear axles were still here cross like axle. Calculating in base 10, the first digit (0 to 9) is on the left and the second digit (10, 20, 90) is on the right. The counting tag was only installed on the right digit.*

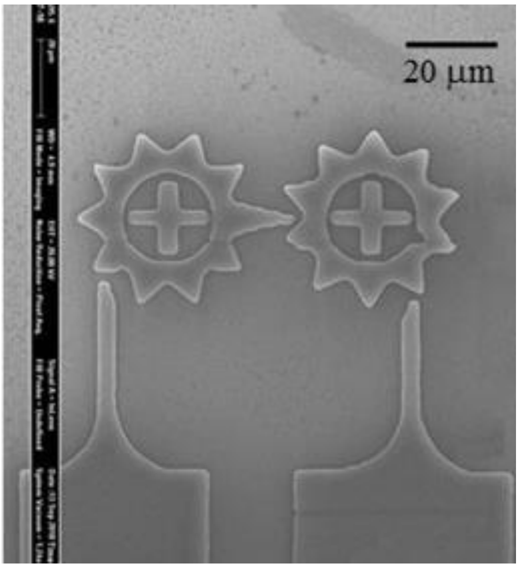

Figure 16: *The complete fabrication on an SiO2 native surface of a 2 stages mechanical calculator respecting the Fig. 15 design. A 8 mm in thickness SU-8 resist was used for a 375 nm UV light. This calculator function with a glass micro-pipette as presented below when fabricated on a graphite on SiO2 supported surface.*

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3.5. THE GRAPHITE ON SIO2 SUPPORTING SURFACE

After a few mechanical manipulations using glass micro-pipette mounted on a micromanipulator under an optical microscope, it became clear that the SU-8 material micro-gears and beams were too adherent to the native SiO_2 surface for reliable rotations. Some micro-gears were broken and it was rather difficult to beneficiate from the lateral elasticity of the micro-beams. Therefore, P2.1 Toulouse had decided to use another surface. The MoS_2 and the graphite surface are known to be quite friction-less. MoS_2 is known to be a nice lubricant and the graphite surface was already used for HSQ meso-wheel manipulation [7]. The graphite surface was selected with a new surface preparation process leading to the production of a very fresh planar graphite surface deposited on a standard SiO2/Si chip. The preparation process of this surface is presented in Fig. 17. The advantage of this process is that the as prepared surface is fresh with very large flat areas as presented in Fig. 18.

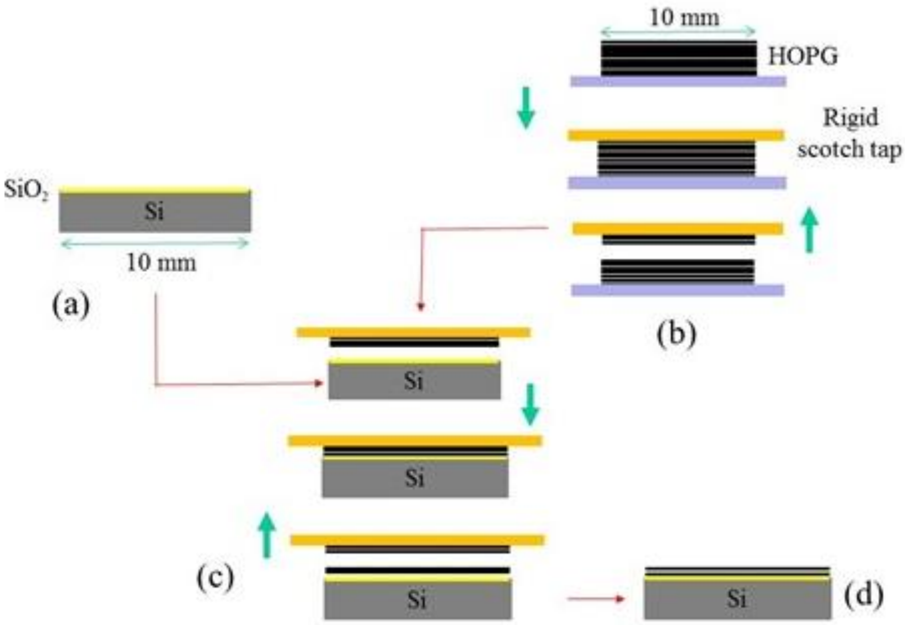

Figure 17: *The P2.1 Toulouse transfer printing process to deposit a fresh graphite surface on a SiO2/Si wafer. (a) The Native SiO2/Si surface wafer is cleaned in acetone and hardly dry. (b) The 3 steps sequence of picking up a layer of graphite from a commercial HOPG bulk sample using a rigid scotch tape. (c) The graphite layer is transfer printed on the decontaminated SiO2/Si surface. Part of the layer remains on the scotch tape and about 8 mm in thickness are deposited on the SiO2/Si surface. (d) This graphite/SiO2/Si surface is ready for optical lithography.*

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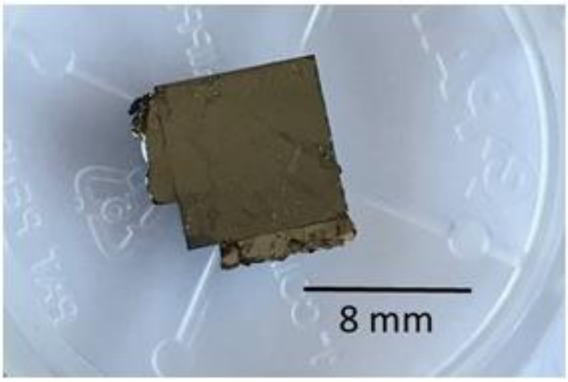

Figure 18: An 8 mm x 8 mm Graphite/SiO2/Si wafer in its plastic protection box produced by P2.1 Toulouse. The average thickness of this fresh graphite surface is about 8 μm measure by ellipsometrie. Lateral left and bottom right are graphite layer going out of the silicon wafer after the transfer printing.

All the scanning lithography processes developed for the SiO_2 surface were adapted by P2.1-Toulouse to this graphite surface. The SU-8 resist was kept changing the development and rising duration not to destabilize the graphite layer. The micro-axel is now made of electro-deposited Ni micro-pillars to anchor them to the graphite surface. The complete mechanical calculator with two calculating stages of Fig. 16was then micro-fabricated in series on this graphite surface as presented in Fig. 19. For comparison with Fig. 16, a zoom is also presented in Fig. 20.

***Figure 19:** Optical microscope image of a series of three 2 stages mechanical calculator with Ni micro-axle micro-lithographed on the graphite/SiO2/Si surface. The cleanness of the graphite surface has still to be improved.*

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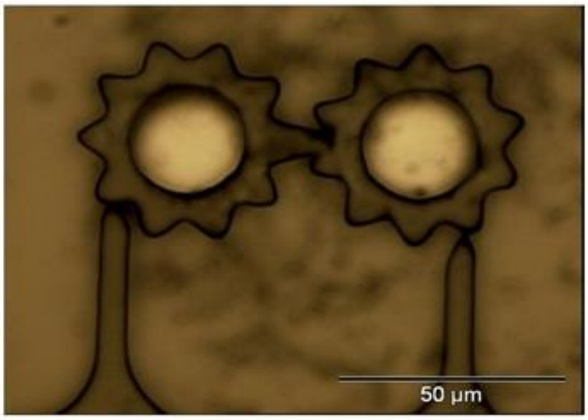

Figure 20: *A optical large zoom in of the Fig. 19 on one of the 2 stages mechanical calculator showing the details of the mounting of the micro-gears on the Ni axles. Notice that this example was chose to show how a to long UV exposure of the SU-8 resist can lead to a merging of all the mechanical part. This is particularly the case here for the long tooth of the left micro-gear which is merging with one tooth of the right one. The end curvature of the beams are also not well defined (see a better insulation in the next section).*

3.6. TESTING THE MECHANISMS

P2.1-Toulouse tested two mechanisms to complete Node 2 and to demonstrate the functioning of two stages of the mechanical calculator shown in Fig. 15: the lateral elasticity of the micro-beam and the transmission of the carry. Both were performed under an optical microscope using a 2 µm apex micro-pipette positioned and manipulated under this microscope using a standard micromanipulator.

For the micro-beam elasticity, the main question was to test the lateral elasticity of a 4 µm in width, 8 µm in height and 45 µm in length micro-beam made in SU-8 baked at 125°C during 3 mm. P2.1-Toulouse has performed lateral deformation test on a lot of those micro-beams. First, a micro-beam needs generally to be detached from the surface. Normally a gentle mechanical push is enough and the optical contrast on its top is changing from grey to white as demonstrated in passing from Fig. 21(1) to 21(2) and it remains (see for example from Fig 22(4) to 22(5)). A lateral curvature up to 40 degrees is not breaking a micro-beam which is enough for a ratchet operation. As presented in Fig. 22(2), already a moderate 5° push is inducing some cracks along the body of a micro-beam. Fortunately, up to 30 to 40 degrees those cracks are stabilized and seems to give more flexibility to the micro-beam structure. Fig. 22 provides a zoom of the 4 cracks observed in Fig. 21. They are nearly equally spaced and are blocked at the same position during the deformation sequence shown in Fig. 21(2) to 21(8). A more detail and systematic study is now required to optimize the lateral elasticity of the micro-beams.

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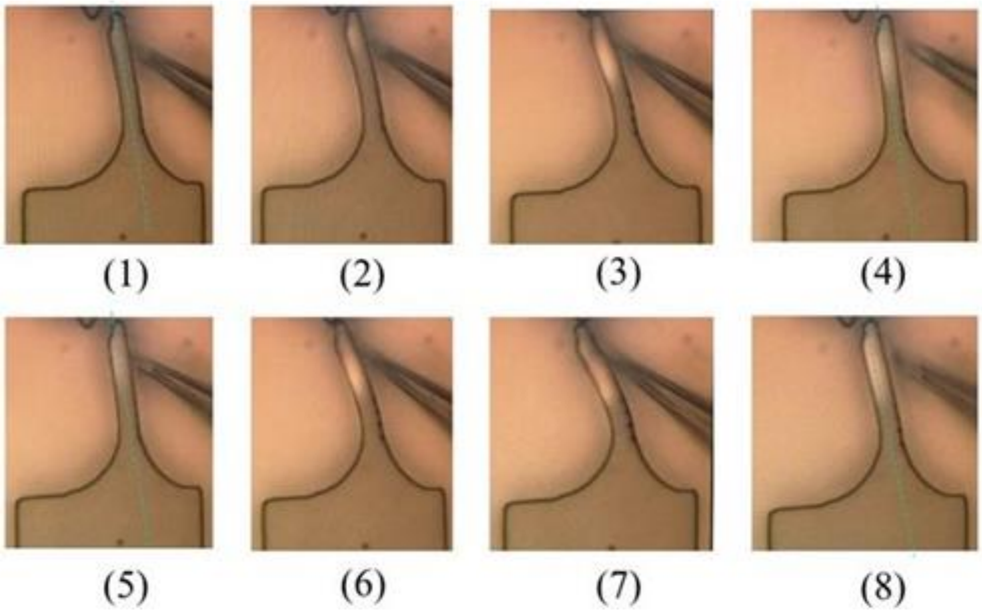

Figure 21: *One micro-beam lateral elasticity being tested by pushing with the 2 mm end apex of a glass micro-pipette. Two sequence are illustrated here. From (1) to (4) a moderate push leading to a 10 degrees of tilt and from (5) to (8) a stronger sequence with a 30° tilt. A zoom on the 4 cracks appearing already on (1) is given in Fig. 22 below.*

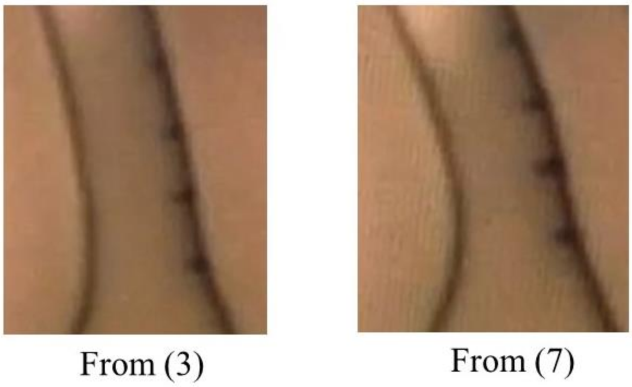

Figure 22*: A detail view on the 4 cracks appearing already in Fig.21(1).*

For the carry transmission, it was important to use micro-gears anchored on Ni axles. In that case the second fabrication process described above was used. The carry transmission was study by P2.1-Toulouse on a two-stages mechanism by first rotating the micro-gear with the appropriate long carry tooth in the position needed to transmit the carry to the next gear. Then, the micro-pipette was used as the stylus used in a macroscopic mechanical calculator to add a “one” to this micro-gear and follow the rotation of micro-gear of the next stage. As presented in Fig. 23, this carry function is working properly i.e. the Ni micro axle are anchored strongly enough to the graphene surface to favour the carry transmission. More important and as anticipated, after a 36° rotation, the micro-gear in charge of the carry is not going backward thanks to the surface friction. This indicates that in the design of the mechanical calculator only one set of lateral beam-ratchet is required.

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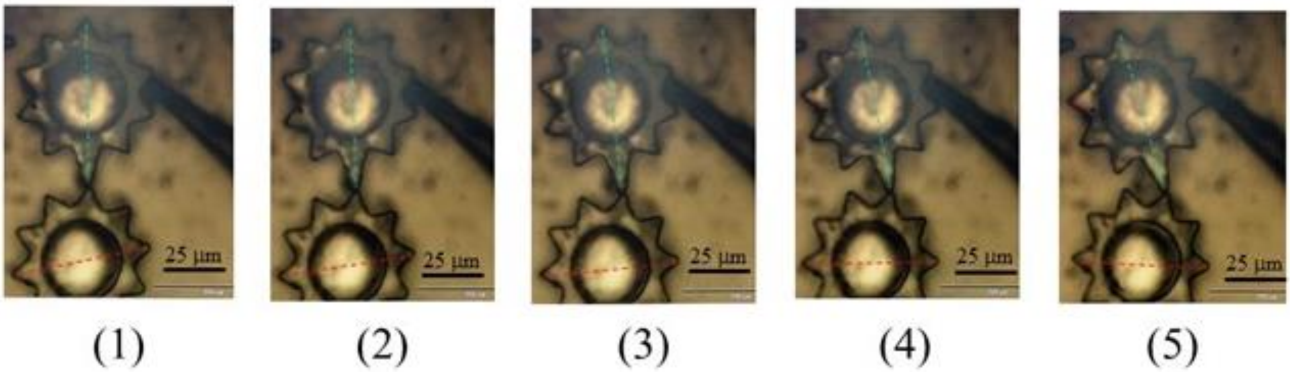

Figure 23: *The demonstration that the carry transmission is working from one stage to the other on a graphite surface with Ni micro-axle. (1), the top gear with its long carry teeth what put to the position to transfer a carry if a 1 is added to the top gear. From (2) to (4) the 1 is entered using the micro-pipette. In (5) the transmission of the carry almost proceed, the down gear had rotated by 1 and the top gear can continue to rotate 9 steps before transmitting again a 1.*

4. CONCLUSION

Starting from the mechanical design of a planar one level millimetre size calculator in Node 1, P2.1 developed a scanning lithography process to miniaturize the structure of a calculator with micro-gears of 50 µm in diameter. This design was adapted for the micron scale and a specific graphene/SiO2/Si surface was developed for mastering the surface friction. Another originality of the process developed by P2.1-Toulouse is that the resist for the lithography is used as material for all the micromechanical pieces. Only the micro-axles are metallic to ensure a good anchoring to the supporting surface. Not only the micro-gears, but also well anchored axles, quite elastic beam-ratchets and lateral pads fixing those beam have been design, fabricated, and tested. To reach Node 2, a two stages calculator was fabricated, which can now be optimized with more calculating stages. The final planar design of Node 2 was transferred to Node 3 for further miniaturization, which will be performed in the next MEMO period.

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