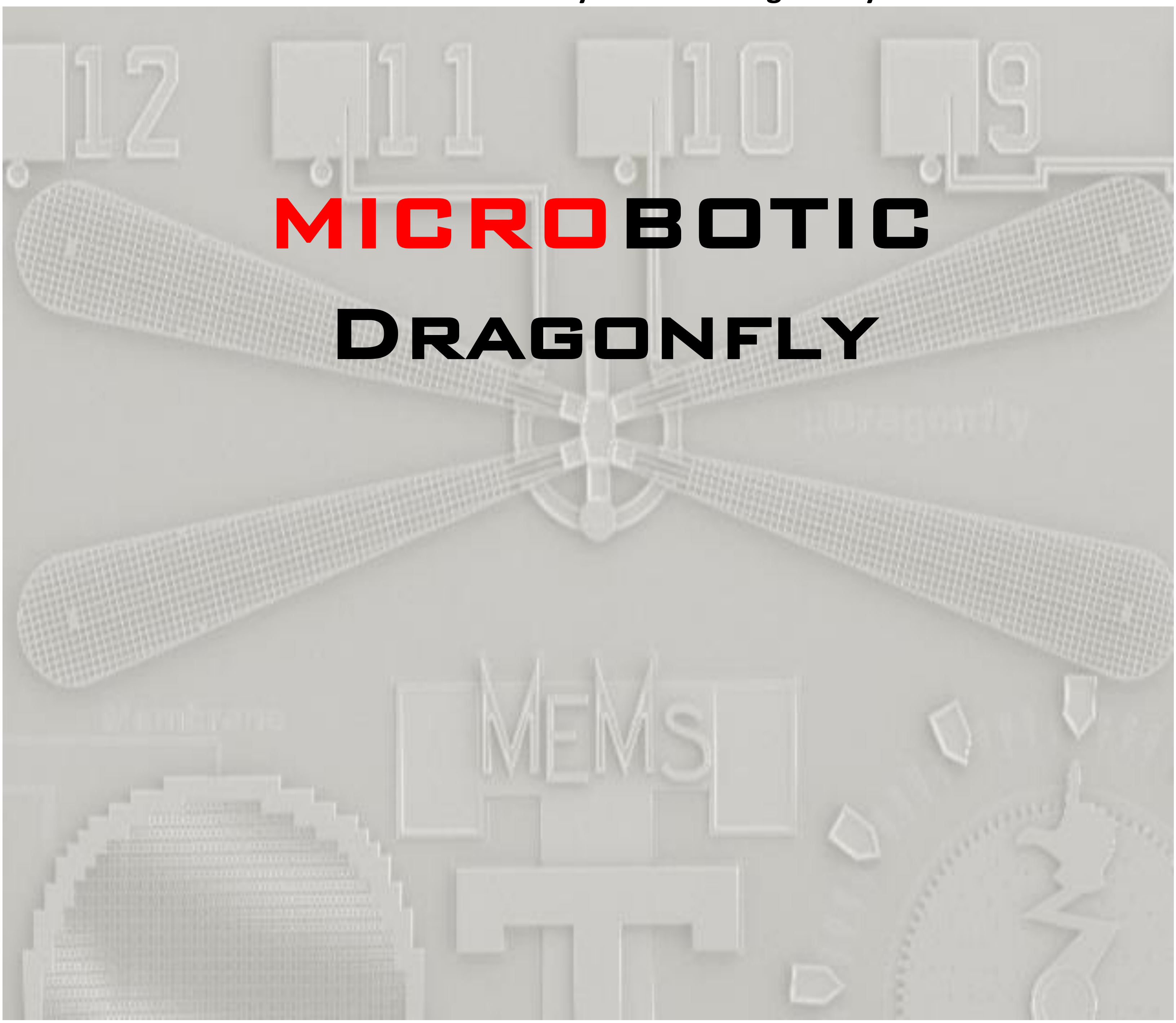
Sandia National Labaratories
University Alliance Design Competition 2011
Texas Tech University – Novel Design Entry

MICROBOTIC Dragonfly



I. ABSTRACT

We describe the design of sub-millimeter air vehicles developed using the SUMMiT V™ fabrication process. These micro-air vehicle designs are based on a functional prototype which was developed by the Texas Tech University MEMS Group. The prototype design integrates dragonfly inspired biomimetic structures with thermal actuation mechanisms to produce flappable wings. This configuration can be used to explore new dimensions in flying microrobots or nano/micro transport devices. The wings in these microstructures are designed to achieve 30µm of vertical deflection. A series of experimental procedures are proposed for device characterization and functionality of the fabricated system.

II. OBJECTIVES

The objective is to produce biomimetic micro-robotic devices designed in the SUMMiT V™ process.

Tasks:

- Design an *on-chip* wing system capable of generating lift
- Integrate the wing system with a cantilever structure to quantify the lift
- Implement a detachable wing system that can be integrated with different platforms for use as stand-alone devices
- Develop an optothermal passive device for un-tethered flight

III. INTRODUCTION

Unmanned air vehicles (UAV) have attained prominence in numerous aeronautic applications spanning both the civilian and military worlds. UAV's are used in surveying enemy locations and recently were used to quantify the amount of radiation leaking from the earthquake damaged nuclear plants in Japan. With the advent of MEMS sensors and the revolution in miniaturization of electronics, the size of robots has also shrunk leading to development of devices like micro air vehicles (MAVs). The MAVs are already of great help to armed forces for sensing and acting upon targets. Further advances will produce additional applications, especially for successful penetration of otherwise inaccessible targets. The recently developed MAVs are inspired by insect flight [1,2,3]. The biological inspired MAV designs generate both lift and thrust by flapping their wing structures to generate aerodynamic forces. Functional designs range in size from 15 cm down to less than a single centimeter. All of them still use macro-sized mechanical parts like motors and gears for achieving motion. There is still much work to be done in the development of MEMS MAVs.

The Air Force Institute of Technology has designed a power scavenging, 500µm optothermally actuated micro robot. These robots are designed to heat and cool asymmetrically so as to rotate and generate lift. Using a 660nm laser to induce actuation, vertical wing tip deflection of 7.2µm was observed [4]. Additional work included biomimetic wing structures that use thermal bimorph actuators made using polysilicon and gold layers to displace 240µm long wings to achieve vertical deflection of 30µm [5].

The TTU designs will be fabricated using the Sandia Ultra Planar Multi-level MEMS Technology (SUMMiT V) process. The strengths of the five-layer poly-Si SUMMiT process will be exploited to achieve the design goals.

IV. DESCRIPTION

Device Design

This work is based on a prototype dragon fly, developed previously by the TTU MEMS Group. Proof of principle has been established with this device. The designs described herein build on the prototype and push us further toward our objective of generating lift and eventually, a standalone flying MEMS robot.

Design of the Prototype On-chip µ-Dragonfly

The prototype dragonfly design spanned an area of 1277µm x 462µm. It consist of four wings which are attached to the thorax (central body). The thorax is rigid *Poly1-2* and *Poly3* structures anchored to the substrate. Each wing spanned 640µm long and 118µm wide (Figure 1). A *Poly3* resistor is attached beneath the *Poly4* wing layer via *SacOx4* cuts to form the heater for thermal bimorph actuation. The SEM image of the fabricated device is shown in Figure 2. When current is passed through the *Poly3* heater, linear expansion of the beam takes place due to Joule heating (Figure 3). As the in-plane motion of the heater is restricted because of the *Poly3-Poly4* connection, linear expansion translates to vertical deflection (Figure 4). The set of *Poly3* beams directly actuates the wing, it is referred to as the *wing actuator*. All four wings are connected in series via a *Poly1/2-Poly3* power rail due to the high power requirements for four wing actuators (Figure 5). As shown in Figure 6, the *Poly4* wing has a mesh structure in order to assist faster heat dissipation, increase the compliance of the *Poly4* wing and reduce the mass. All will help achieve greater, out-of-plane motion by the wing actuator. The dimples are provided at the wing tips using *Dimple4* cuts which prevent the wings from snapping down to the substrate due to stiction. We achieved vertical deflection of ~20µm actuating at 200mW. The microscope images upon actuation of this device are shown in Figure 36.

Dragonfly Wings

After testing the prototype, it was realized that for a micro-robot to produce lift, some asymmetry must be introduced between the downward and upward strokes. This could be potentially achieved by providing a curvature to the wing so that it is relatively more aerodynamic for the upward stroke compared to the downward stroke. This condition will increase the upward thrust [6]. We decided to combine biology inspired wing designs and thermal actuators to produce flapping wings. Amongst countless number of insect species having the ability to fly, we chose to mimic dragonfly wings for one primary reason. Dragonflies achieve fight by flapping their wings in the vertical direction, whereas most of the other insect species move their wings back and forth or in a rotary fashion to create a bound vortex. From the study of forces involved in micro-robotic flight, it was determined that the most dominant design parameters are deflection, surface area, and mass [6]. The wing actuators are modeled in a FEA tool and optimized to generate maximum out-of-plane deflection. It is also important to keep the mass to a minimum while increasing the surface area. Larger surface area helps generate more thrust, as well as reducing the time required for cooling the electrothermal actuators by convection. Having a shorter cooling time for the device will allow operation of the device at higher frequency input-pulses, which in-turn could increase the upward thrust. Apart from this, the new wing designs exploit the bending caused by the as-deposited residual stress of the aluminum layer over the existing polysilicon wing structure. Figure 7 shows similar wing designs which are implemented in three variations: a) Anchored Dragonfly b) Cantilever attached Dragonfly, c) Detachable Dragonfly, and d) Detachable laser powered Dragonfly

Anchored Dragonfly

The anchored dragonfly is a modified design of the on-chip prototype and it is shown in Figure 8. The central body/thorax is anchored to the substrate. The *Poly4* wings are made in such a way that they will provide maximum air resistance on the downward stroke. In an attempt to do that, we have provided them with minimum etch release holes on the wing (every 25 µm, linear). To generate more aerodynamic force by the wings, multiple Al strips have been included. The difference in the coefficients of thermal expansion (CTE) between Al and poly-silicon can lead to residual stress during the fabrication process. In the SUMMiT V ™ process, residual stress exists between the low CTE *Poly4* layer and the high CTE aluminum layer. This residual stress will result in vertical deflection of the stacked *Poly4-Al* layer. It is estimated that having wing dimensions of 525µm will lead to ~6µm of deflection due to residual stress. When the temperature of the heater beam rises to the fabrication temperature, the metal expands to curl the wing downwards. In electrothermal devices, the heating cycle can be much faster than the cooling cycle. The upward wing stroke will be more aerodynamic than the downward stroke providing the required asymmetry for lift (Figure 9). The principle of the upward stroke still utilizes the same wing actuator from the prototype for the upward stroke while providing more air resistance during the downward stroke. Furthermore, as a modification to the prototype wing design, the *Poly3* heaters are placed along the edge of the wing extending to its apex. Figure 12 shows the comparative designs for dragonfly and our design. This will act as the *costa* and s*ubcosta* veins proving a strong leading edge enabling the wing to become an airfoil-shaped body as present in the actual venation of the dragonfly wings. The lower wings have a typical airfoil shape with a rounded leading edge, followed by a sharp trailing edge having an asymmetric curve. As shown in Figure 11, a *Dimple3* cut is provided on the bottom to avoid contact of the heater to the *Poly0* layer below, thereby minimizing stiction issues. Apart from aerodynamic criticalities, we need to make sure that the electrical contacts for the wing actuators are immaculate in our design. The electrical path is made by stacking *Poly1-2* and *Poly3* to pass the required amount (estimate: ~60mA) of current though it. The calculated power consumption over the prototype was 200mW and is expected to be similar for this design. Wings are separated from the central body by providing a 1µm cut to avoid short-circuiting via the body, enabling the synchronized stroking of forewings and hindwings.

On-chip Dragonfly Attached to a Cantilever

As shown in Figure 13, the dragonfly has been mounted on cantilever structures that also serve as electrical conduits. The idea behind doing this is to quantify the aerodynamic forces generated when powering the wing actuators, by quantifying the deflection of the cantilever using an optical interrogation system. The wing design remains the same except the root is now enclosed in a garage structure. At the root, (Figure 15) the wing is enclosed in the garage structure made from *Poly1-2* and *Poly4* while the wing is brought down to the *Poly3* layer via an interconnect before the garage structure. The *Poly4* wing is supported by four beams. In the forewings, the support is provided over the chord of the wings where maximum torque is expected. Two beams support the leading and trailing edge of the wing and the other acts as a reinforcement frame for the *Poly3* heater beams. The power rails are now made by stacking *Poly3* and *Poly1-2* which are joined by multiple concentric *SacOx3* cuts, thereby increasing the overall volume of the rails allowing higher currents to pass through. Upon actuating the device at optimal frequency and power, the lift generated by the device can be quantified by measuring the change in angle (Φ) with a laser. Figures 16 and 17 show the details for sensing the deflection.

Detachable Dragonfly

The TTU MEMS group has experience in designing, testing, and utilizing detachable cantilevers [7] and detachable micro-grippers [8]. The basic motive behind designing a detachable dragonfly is to transport the device to another substrate to test alternate power sources. The bond pads include the electrical connection sites and handling sites. The height of the connection sites and handling sites is 11 µm. The bondpads, shown in Figure 18, incorporate layers *Poly1-4*. The electrical connection sites are the regions where external power is fed to the wing actuators. An array of 2 x 2 µm poly-silicon cuts are used in the electrical connection sites. These act as etch release holes in the fabrication process. Each electrical connection site has a 1 µm diameter via from *Poly1* to the *Poly0* layer. Figure 19 also shows a cross-section view of a via in one of the connection sites. Apart from this via, no other portion of the dragonfly is anchored on the *Poly0* layer. Vias can be broken by a sufficient magnitude of external handling forces. External probing/grasping devices can be used to detach the dragonfly system from the two vias. The detached dragonfly can be manipulated and assembled on another substrate.

One of the main challenges that micro scale flying devices face is providing power to such a small device without restricting it to a tethered power source. Photovoltaics could be a promising technology for powering MEMS devices. Previously Hollar *et al.* utilized an array of 90 solar cells in series to produce 100µW of power with each cell requiring only 150μm^2 of space to power a miniature robot [9]. There has been development of thin-film batteries by Oak Ridge National Labs (ORNL) which has the capability to generate 100mW per 90x150μm^2 [10]. By advancement in CMOS technology in the future, integration of such high power batteries might be possible with SUMMiT V™ devices. This could possibly allow us to attach multiple cells to the bondpads of the Dragonfly to operate in standalone operations.

Passive Dragonfly

As discussed previously, residual stress exists after deposition of an Al film over a polysilicon layer (Figure 20). This stress will result in a vertical deflection. The negative effect of this phenomenon can be exploited if we are able to achieve downward deflection when heated with a focused laser. In the presented design (Figure 21), the thorax is made using stacked *Poly1-Poly4* layers. Increasing the thickness of the laser target ensures maximum photon energy conversion to heat and hence boosting energy absorption efficiency. As the *Poly3* and *Poly4* layers in SUMMiT V™ are planarized by CMP we need to make some additional changes to try to minimize reflection. The topmost *Poly4* layer is perforated by providing *Poly4* cuts and *Poly3* under it is attached to the *Poly1-2* laminate by multiple vias made by *SacOx3* providing spacing of 1µm between them. Because of the non-ideal aspect ratio present in the deposition process, the *Poly3* deposited now has a non-planar surface. As shown in Figure 22, the perforated *Poly4* allows the light passing through it to hit the *Poly3* under it. The *Poly3* layer disperses the light and most of it is trapped between the two layers (Figure 23). Szabo *et al.* have successfully demonstrated the optothermal actuation mechanism in bent beam electrothermal devices [11]. The body of the dragonfly is the target for the laser and the width of it is 80µm which will allow use of an 80µm spot size laser. The wings are attached to the central body on the *Poly4* layer. The metal strips are arranged in a fashion that helps achieve maximum warping caused by CTE-mismatch between the Al-Poly layers in post-release and post-actuation.

SUMMiT V™ Strengths

The SUMMiT V™ process provides a large number of independent *flat* layers produced by chemical mechanical polishing (CMP). Flatness is required for flappable wing designs that include polysilicon heater elements, which can be placed one-above the other. The gap provided by the SUMMiT process is just enough to provide the air-layer required for cooling and hence the high actuation cycles rates of the electrothermal devices. The thicknesses of the layers (esp. *Poly3*) provide enough resistance and thickness to produce the right amount of thermal expansion with necessary compliance in the beam. This attribute also helps to achieve the right amount of vertical displacement in all electrothermally actuated devices. *Dimples* provided on layers *Poly4*, *Poly3* and *Poly1* help reduce total stiction. The deposition of a 0.7µm thick aluminum layer over polysilicon develops residual stress which is required for providing aerodynamic shape to the wings of the dragon fly. This layer also increases the current carrying capacity through the traces.

Usefulness of Design for Educational Outreach

Device such as the *Dragonfly* can act as a platform to spread the concepts of the micro and nano world to many levels of students.

- *Grades 7-12:* In childhood, everyone is amused by flying objects. Demonstrating a micro-dragonfly will be attention getting and intriguing to students. Many questions will be generated regarding how it works. This can lead to teaching a variety of physics concepts. Demonstrating our micro-dragonfly system to grade school students will be useful in educating them in size scaling factors. The micro devices can be compared to biological cells, small insects, and of course a dragonfly. It provides an amusing way to promote engineering to prospective students. To actually help students *feel* the flapping movement of the actuators, we will connect the control of the device to a haptic. Haptics utilize tactile feedback to provide mechanical response to the user by scaling the micro/nano forces to macro level. A commercially available gaming haptic will be interfaced with the proposed device. The force feedback will be simulated with each actuation cycle (LabVIEW routine) of the wing actuator giving a feeling of upward and downward strokes. A demonstration of a similar system was given at Lubbock's science museum on Nano Day 2009 (Figure 34).
- *College freshman engineers/physicists:* The device can be used to explain concepts of *thermodynamics* such as thermal expansion, contraction and heat transfer modes by displaying the operation of electrothermal actuators used in the design. The thermal expansion could be determined by measuring out-of-plane deflection.
- *Graduate students:* Lab experiments can be designed for quantifying the performance of multi-level devices. The device could also be used to exhibit the strengths of SUMMiT V process providing good insight into multi-layered structures and surface micromachining (SMM) technology. Performing micromanipulation and handling of the detachable dragonfly would interest graduate students and help further its potential applications to the fields of biomolecular manipulation and microassembly.

V. PRINCIPLE OF OPERATION

1. On-chip anchored dragonfly characterization

The system is driven by simultaneous actuation of all the polysilicon heaters. The linear expansion of the heater takes place due to Joule heating. This linear motion is now translated to vertical deflection of the *Poly4* wing as it is joined to the *Poly3* layer. The *Poly4* layer remains at a much lower temperature than that of the *Poly3* beams as it is only heated due to convection, whereas the latter reaches much higher temperatures (~500°C) because of Joule heating. The rise in temperature of the *Poly4* layer is utilized as it helps warping the wings due to presence of Al strips in the diagonal pattern. This causes the wings to curl downwards in upstroke and curl upwards during the downstroke, (shown in Figure 9) producing aerodynamic force.

2. Dragonfly attached to cantilever characterization

The basic theory of operation is shown in Figures 16 and 17. The dragonfly design is similar to the one which is anchored *on-chip*, except the wings are now in a "garage" structure. This feature allows the wings to achieve electrical isolation from the body as well as more deflection by reducing the stiffness in the *Poly4* beams. The wings now completely rest on a *Poly3* resistor attached by a *SacOx4* cut. The cantilever structure is provided with a *Poly0* layer beneath it which forms a parallel plate capacitor with the suspended *Poly4* layer. Upon pulsing the wing actuators, the lift can then be calculated by measuring the deflection in the cantilever beams. The characterization of the deflection can be done optically as well as by monitoring capacitive changes. The presence of the metal layer on the *Poly4* suspension helps improve optical properties for laser interrogation and also increases the current carrying capacity of the structure.

3. Detachable dragonfly characterization

The primary goal of this aspect of the work is to develop an assembly process for producing a standalone dragonfly which could scavenge energy from the environment or carry a very small power source. To carry out this work, a micro-gripper based manipulation system will be used that has been demonstrated to manipulate micro-beads in our prior work [8]. Figure 30 shows the system with three major parts, (i) 3-axis manipulator system, (ii) commercially available electrostatic microgrippers from Femtotools (FT-G100, FT-G60), and (iii) haptic controller.

The proposed experimental setup for handling the dragonfly is shown in Figure 31. The MEMS chip is on 2-axis stage. The FT-G60 microgripper is used to grasp the individual dragonfly and the 3-axis system (haptic) controls the microscale positioning and manipulation of the dragonfly. Texas Tech MEMS had developed a detachable microgripper (Figure 32). Figure 33 shows the pick and place operation of a detachable microgripper which was transported to another printed circuit board and later was successfully actuated.

4. Optothermal dragonfly characterization

Optothermal actuation will provide an alternative non-electronic actuation example that could prove to be a stepping stone in the making of autonomous devices. First of all, the devices could be detached from the substrate as the whole dragonfly structure rests on two, 1µm x 1µm vias. Here, laser heating is the key to actuate and generate thermal energy in the thorax which causes an increase in temperature across the wingspan. Material bimorphs formed by aluminum over *Poly4* were chosen because they could take the most advantage of this concept. The design is capable of absorbing the most laser energy (as described in Figure 23). The upward and downward curling of the wing in the "off" state and the "on" state respectively helps us provide asymmetrical wing motion for upward and downward stroke. A 660nm laser diode could be used for this in a pulsed mode as it is capable of providing the power of 60mW.

Measurements and Experimentation

The primary measurements will focus on the motion characterization of the *μ-dragonflies*. The optical characterization will be done by utilizing the experimental set-up as shown in Figure 35. It will consist of an interferometer and custom built power supply unit. A LabVIEW VI will be developed to control the devices through a GPIB interface. The tests will evaluate and quantify minimum, maximum, and optimal values for operating parameters of wing actuators. The technique of Raman spectroscopy could be used to monitor the temperature changes in the electrothermal actuators and estimate the heat generated by photon absorbance in laser actuated dragonflies. Finally, to complete thorough characterization of a dragonfly, we can gauge the amount of deflection of the cantilevers due to lift-off optically.

VI. MODELING

The flapping of the wings in the structure is due to: a) The difference in stress resulting in vertical deflection and b) the wing actuators. To accurately predict future device performance; downward deflection of a polysilicon cantilever coated with an aluminum layer is modeled in the CoventorWare® finite element modeling package. A Manhattan brick mesh, with an element size of 5 μm in the planar dimensions and 0.5μm in the extrude direction, was used in the model. It was observed that for a 600μm long cantilever structure at 600K, there was vertical deflection of 6.7μm. Figure 26 shows the displacement vector sum of the cantilever beam in the downward direction. The wing actuators are the most important component of the wing design and the one which govern the operation. To obtain the understanding of device physics and their performance, the wing actuators were simulated. Complete three-dimensional actuation of the device is modeled using an extruded brick mesh type with a split and merge algorithm having parabolic element order. The model is a coupled-field electrothermomechanical model with conductive heat flow due to Joule heating and displacement due to the thermal expansion is calculated. Figure 27 shows the displacement magnitude (30μm at 10V) for the heater arms in x-axis which translates to Z-deflection in the actual design. The graph is plotted for the vertical deflection values with respect to voltage in Figure 28.

Important aerodynamic parameters like drag force, lift force, and Reynolds number for the design are also calculated for forewings and hindwings and compared with the previous work done by Coleman *et al*. [5]. The results are tabulated in Figure 29 and clearly demonstrate the merit of the presented design. Finally, the optical absorption and conversion from a 660nm laser beam was calculated to be 30-40%.

VII. SUMMARY

We have designed a micro-robot with flappable wings biomimicing the dragonfly. These devices use the eletrothermal actuators for achieving the vertical displacement and wings develop the aerodynamic shape using the Poly-Metal CTE mismatch. The developed devices have capability to work on and off-chip which gives them the potential to eventually work in remote environments. The actuation system is designed to have high efficiency by utilizing the strengths of SUMMiT V process. Experiments will be conducted to characterize and test the proposed device. For each wing, the device is expected to operate at ~150Hz and gives the wing tip deflection of 30μm. The analytical calculations for the aerodynamic forces show that these devices are at par with present MAV devices.

VIII. FIGURES

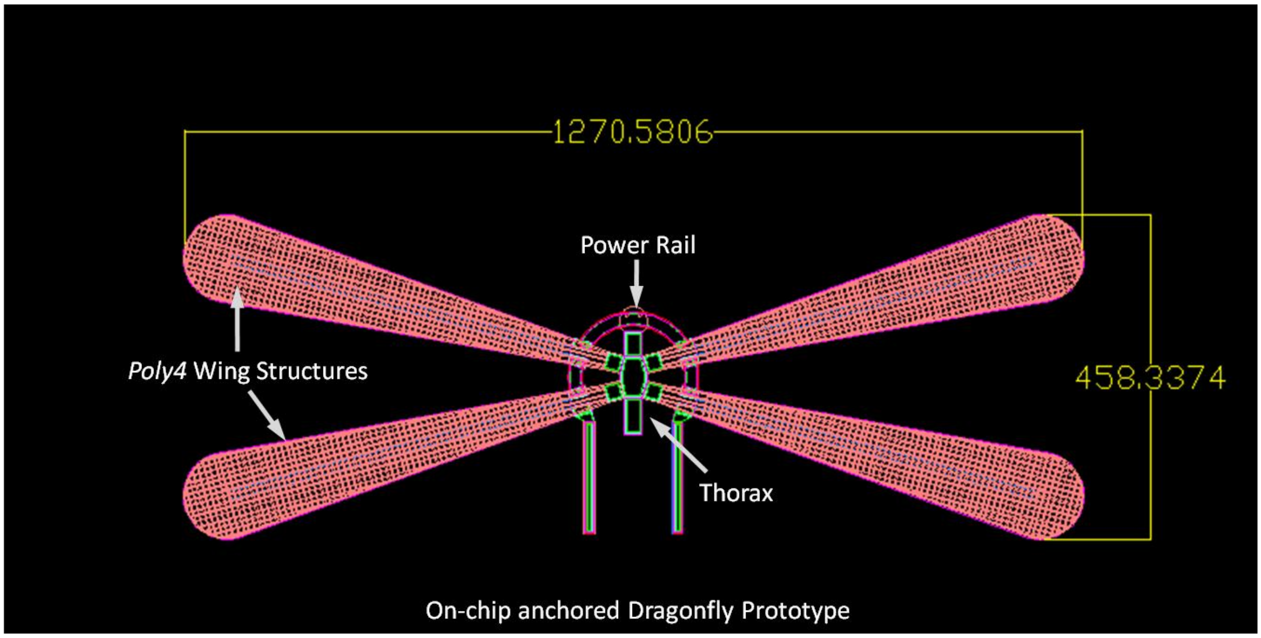


Figure 1. AutoCAD 2D layout for *μ-Dragonfly* prototype.

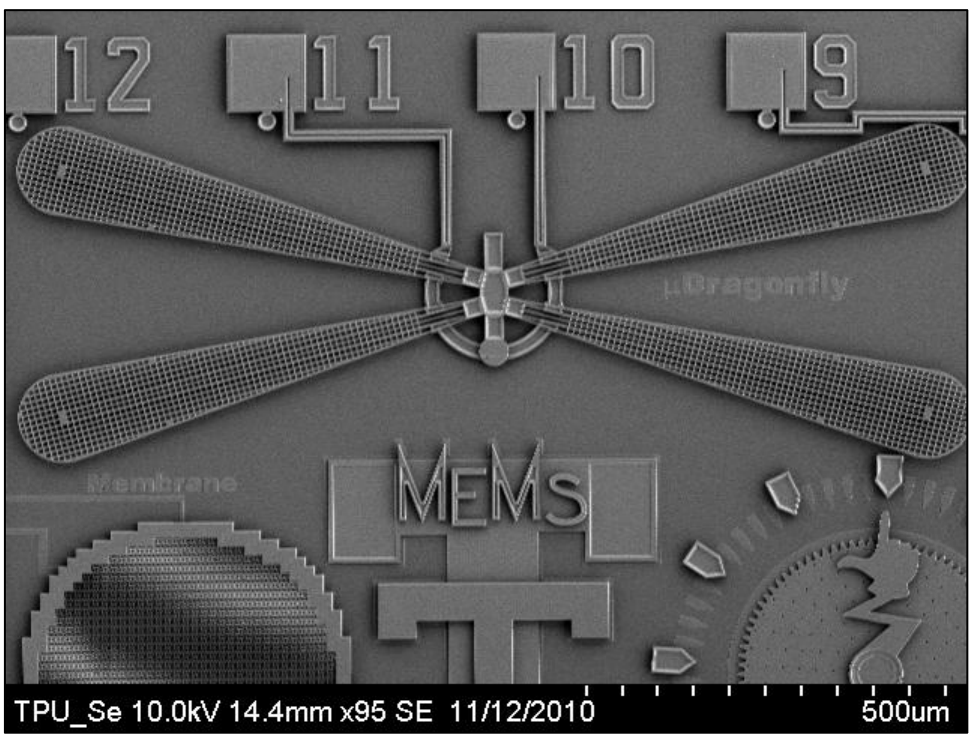


Figure 2. SEM image of *μ-Dragonfly* prototype.

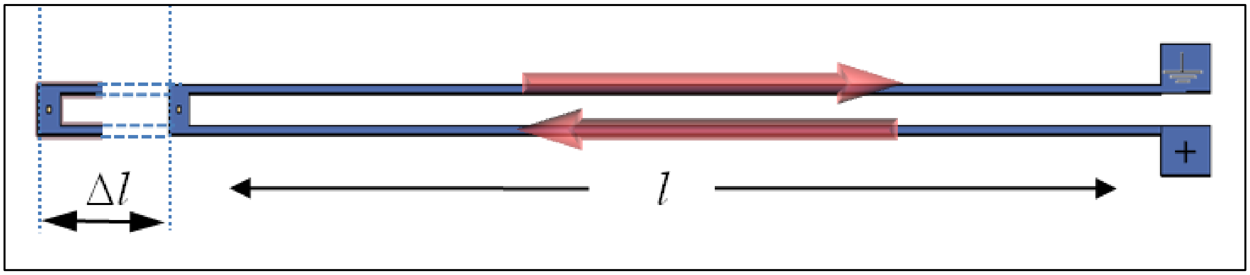


Figure 3. Linear expansion taking place in *Poly3* wing actuators post actuation.

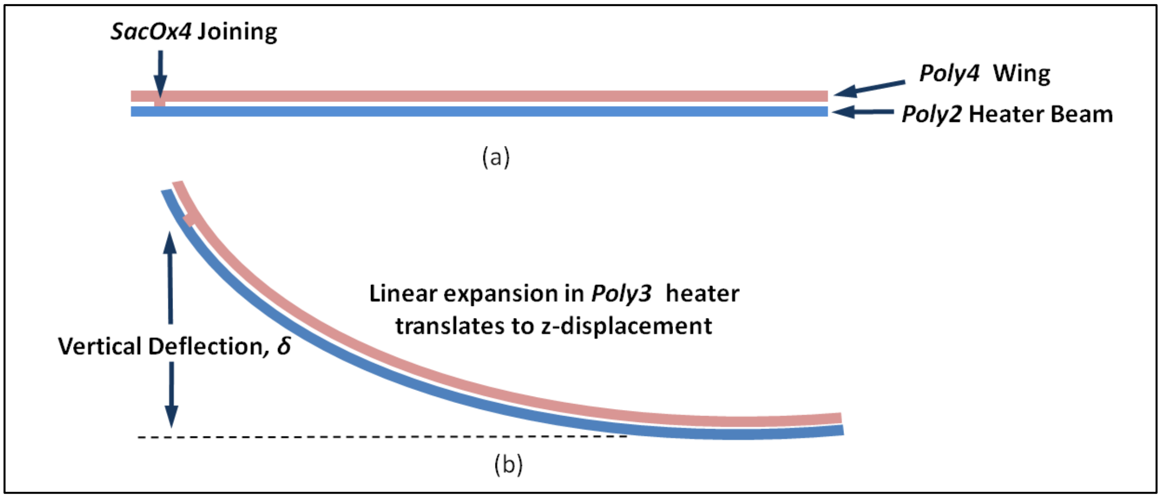


Figure 4. Linear expansion in *Poly3* heater beam translates to vertical deflection post actuation.

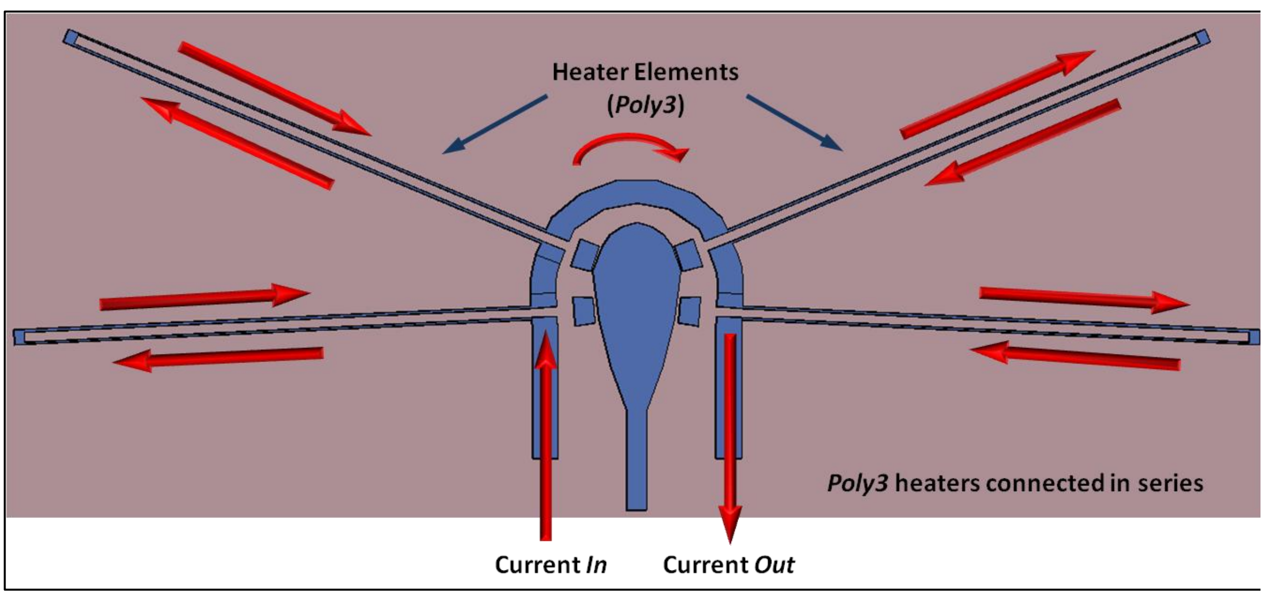


Figure 5. 3D view of *Poly3* series electrical connection scheme.

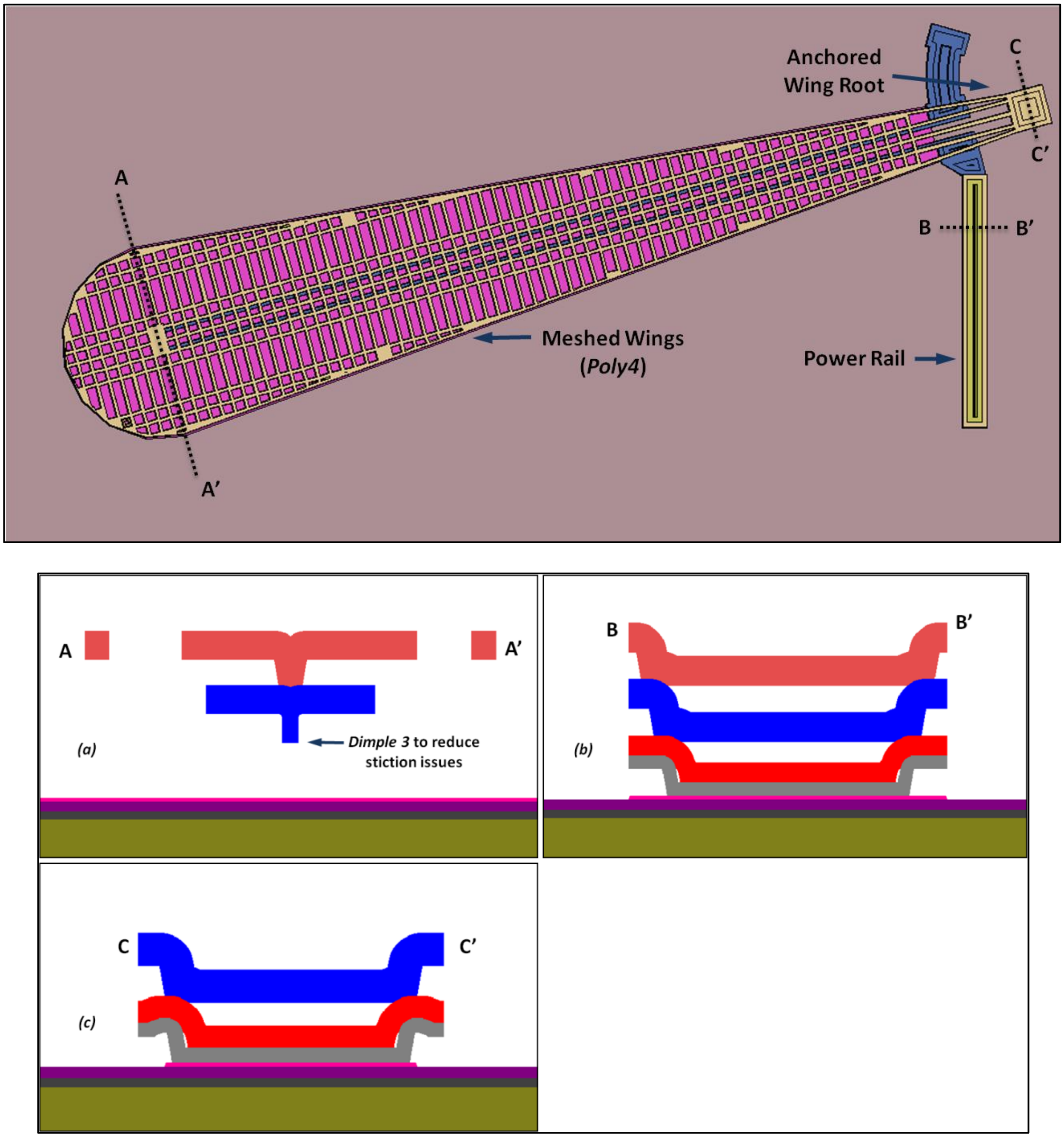
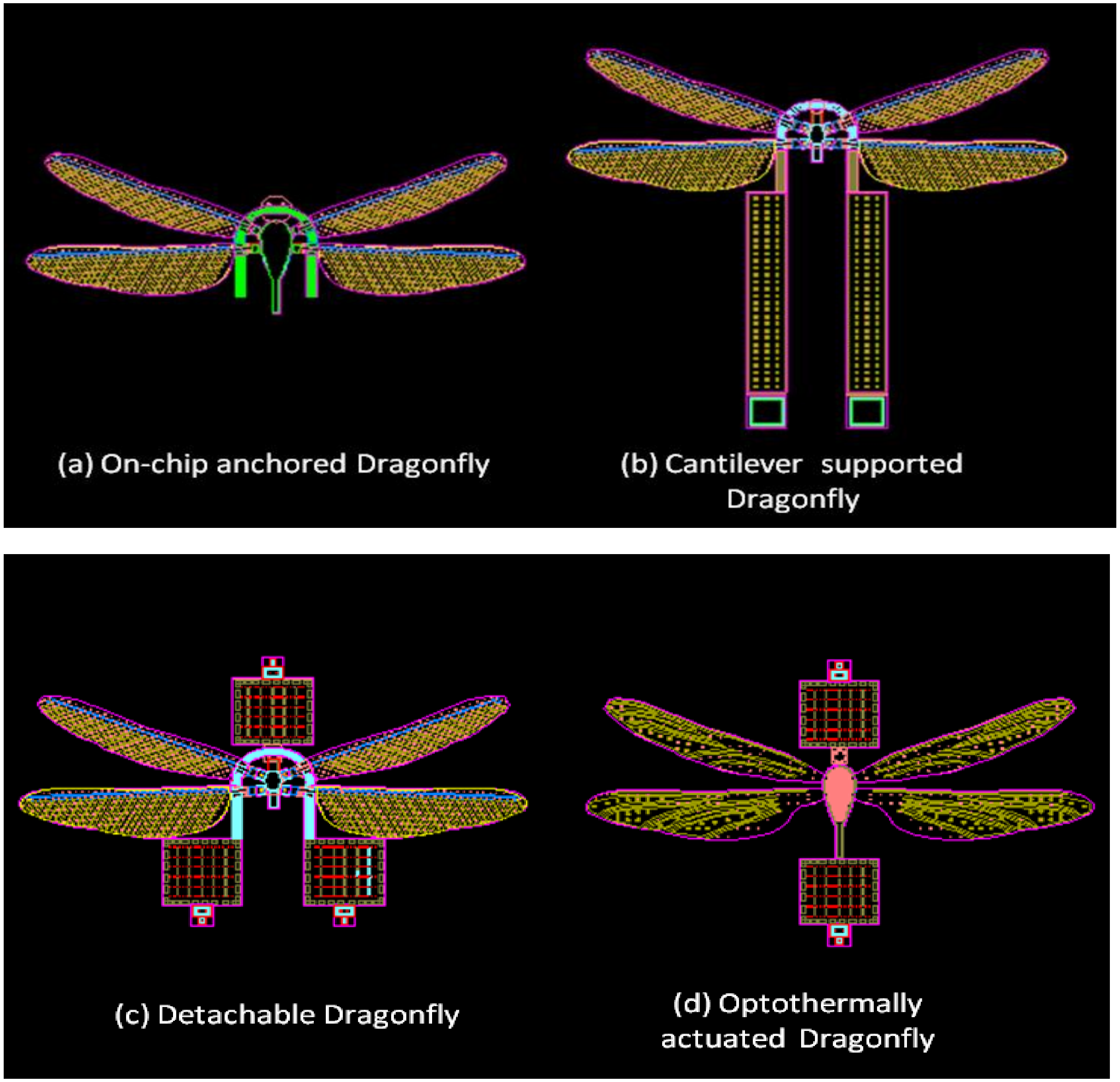
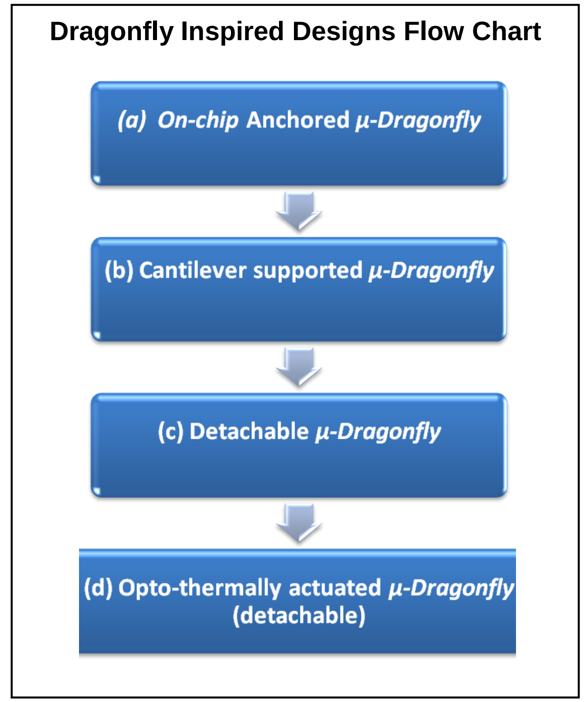


Figure 6. 3D model of prototype wing with various cross-sections. (a) shows the dimple under the wing, (b) *Poly0-Poly4* power rail and (c) Anchored wing root.





A step by step approach from on-chip actuated designs to stand-alone designs

Figure 7. AutoCAD 2D layout of Dragonfly Designs.

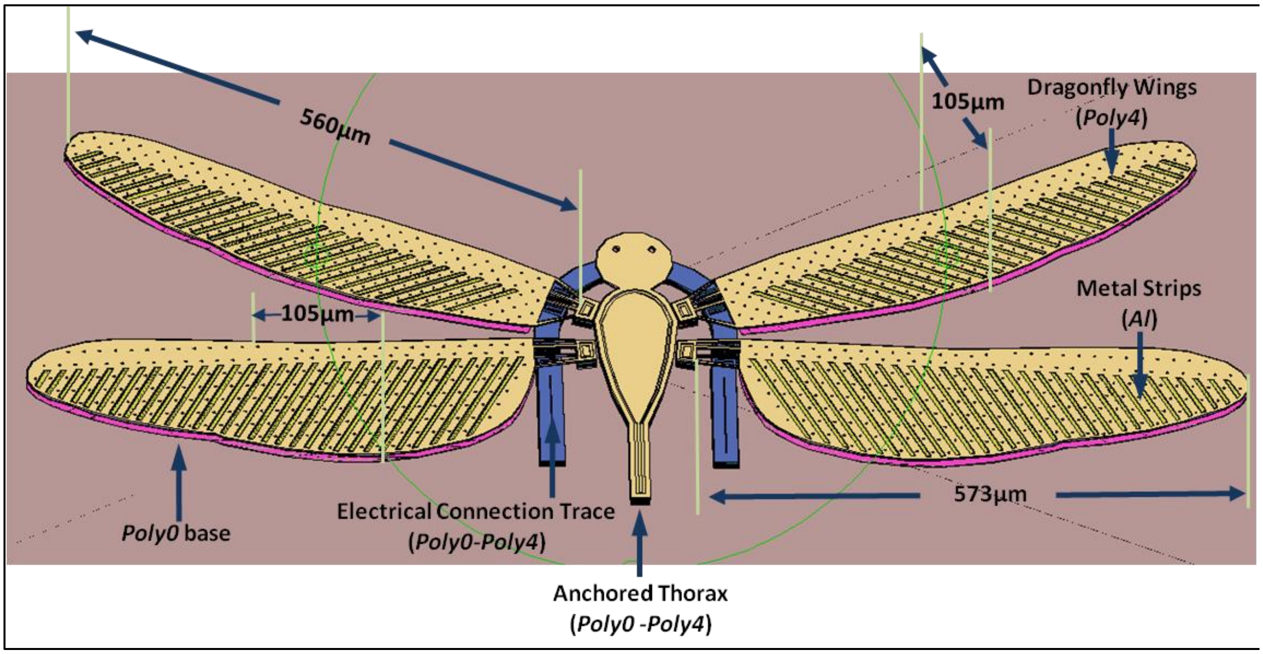


Figure 8. 3D view of anchored dragonfly design.

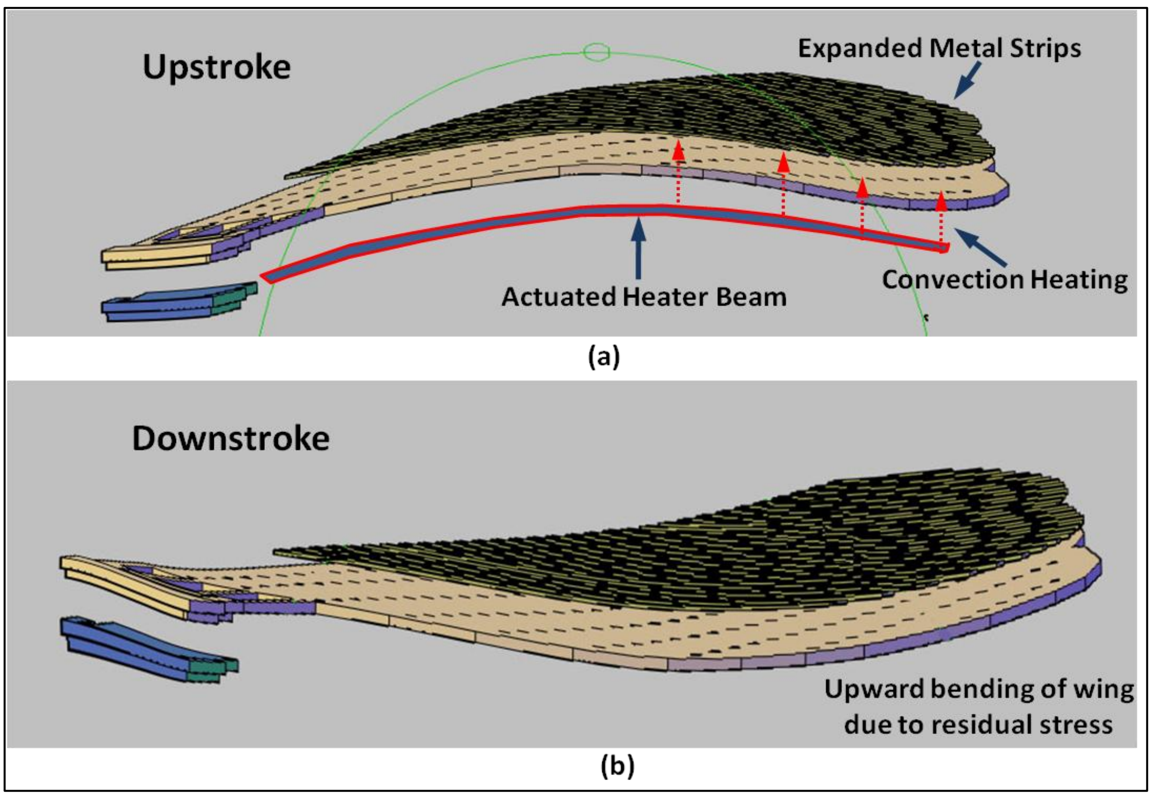


Figure 9. A scaled 3-D model showing wing shape for up and down-stroke. Aerodynamic wing shape is achieved upon actuation as the metal strips on wings causes the wings to curl downwards whereas during downstroke the wing slightly curl upwards.

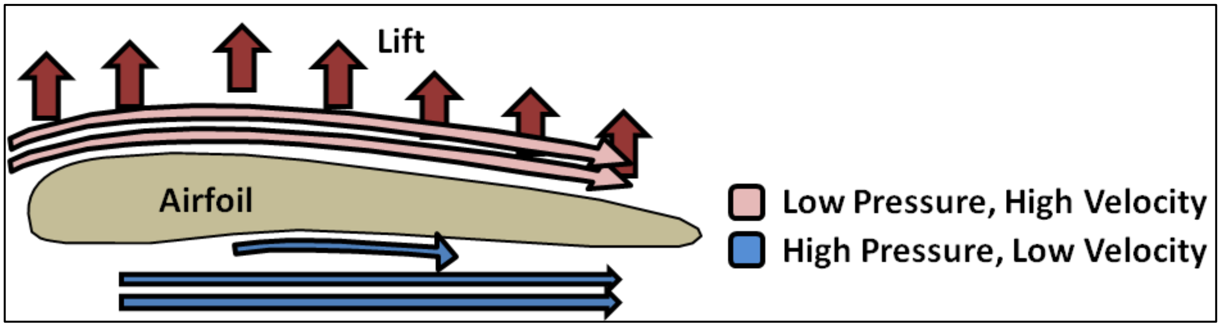


Figure 10. Conceptual diagram for airfoil theory. Lift is a result of differential pressure caused due to high velocity laminar flow over the airfoil and low velocity flow under the airfoil.

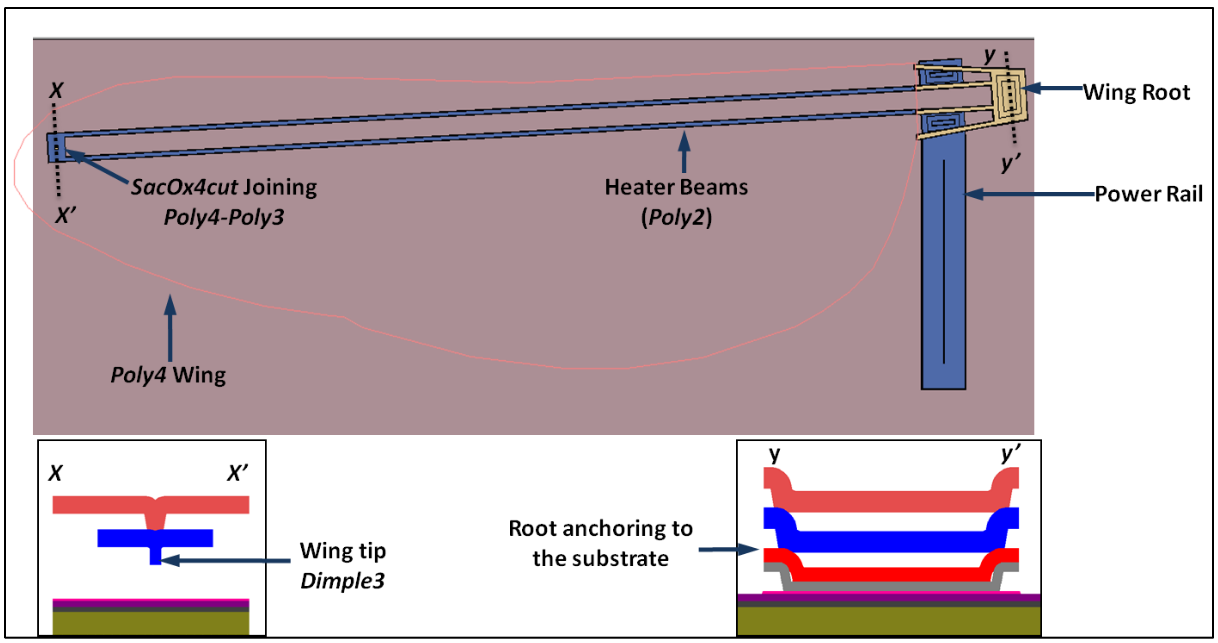


Figure 11. 3D view of anchored dragonfly design without *Poly4* wing structure showing *Poly3* heater beams, the wing root cross-section and wing tip.

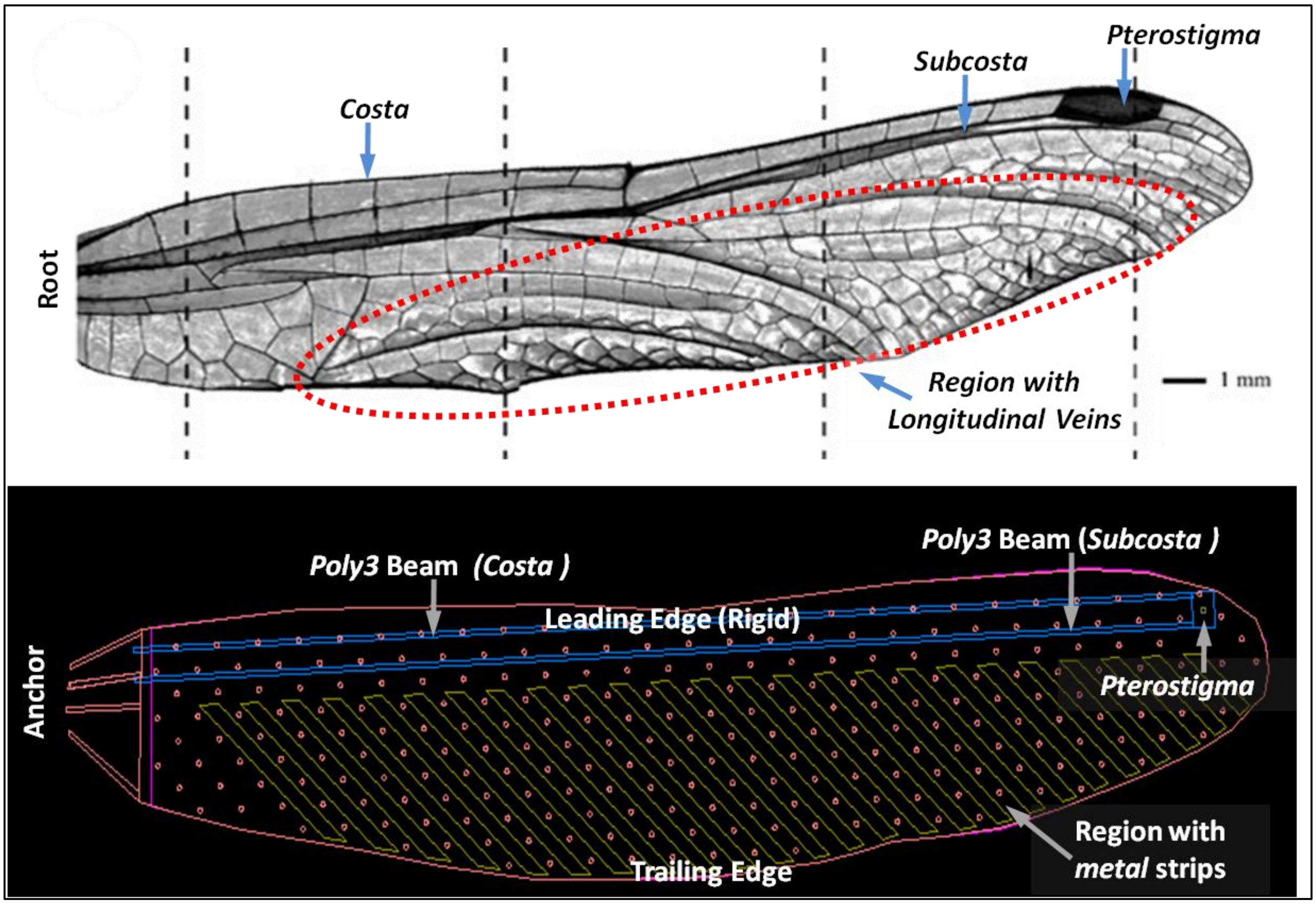


Figure 12. Forewing Comparison of Dragonfly wings with actual Dragonfly. Heater beams act as *rigid* veins in dragonfly wing forming leading edge a stronger leading edge for wing.

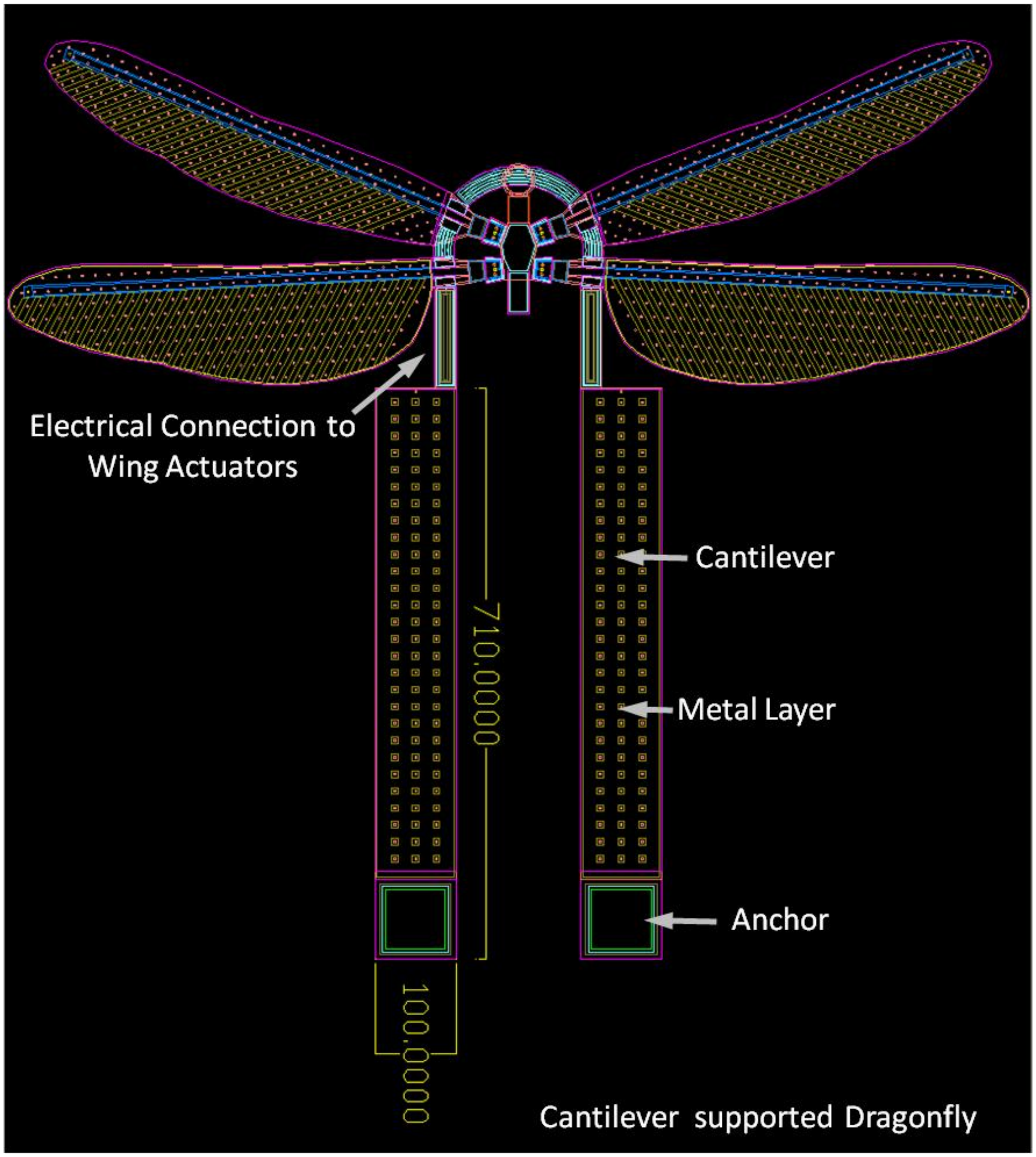


Figure 13. AutoCAD 2-D layout of Cantilever supported Dragonfly.

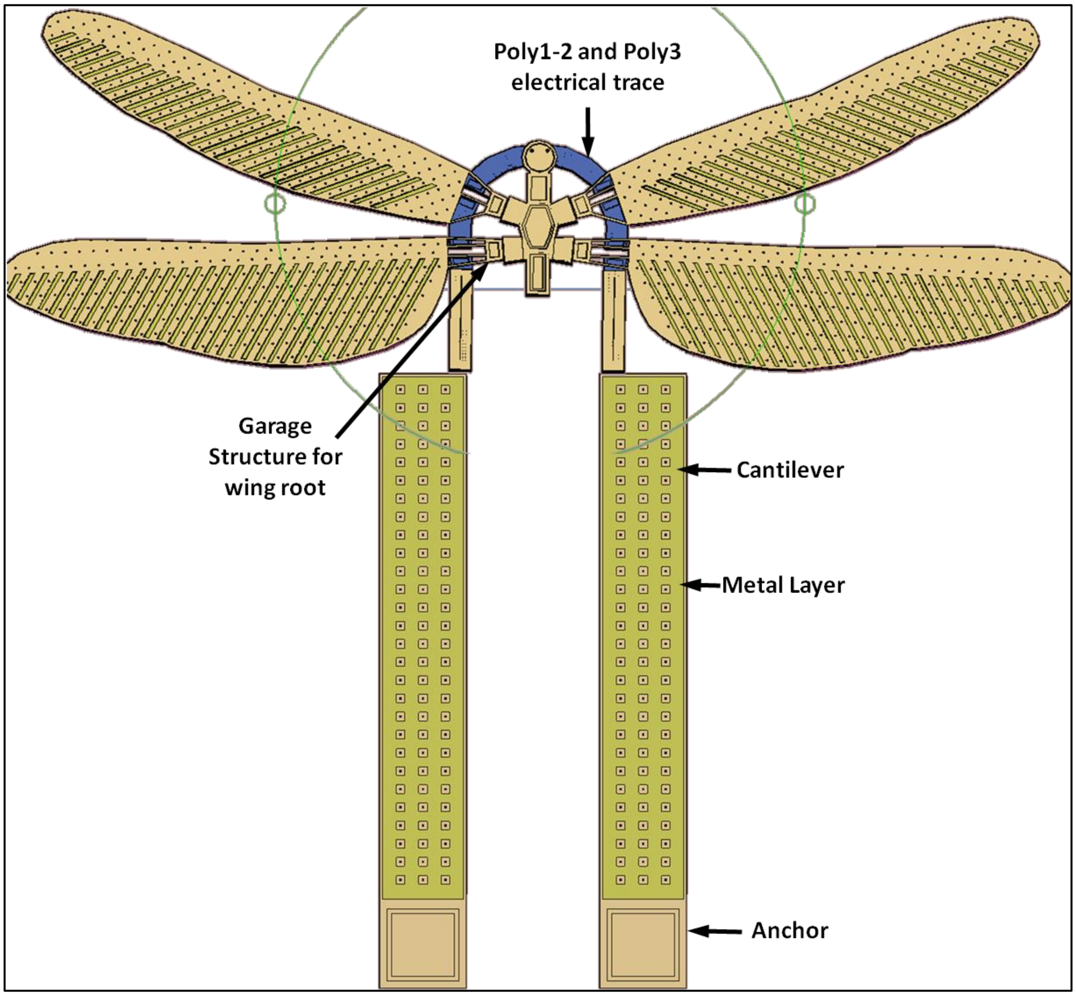


Figure 14. Topview of 3-D model of Cantilever supported Dragonfly

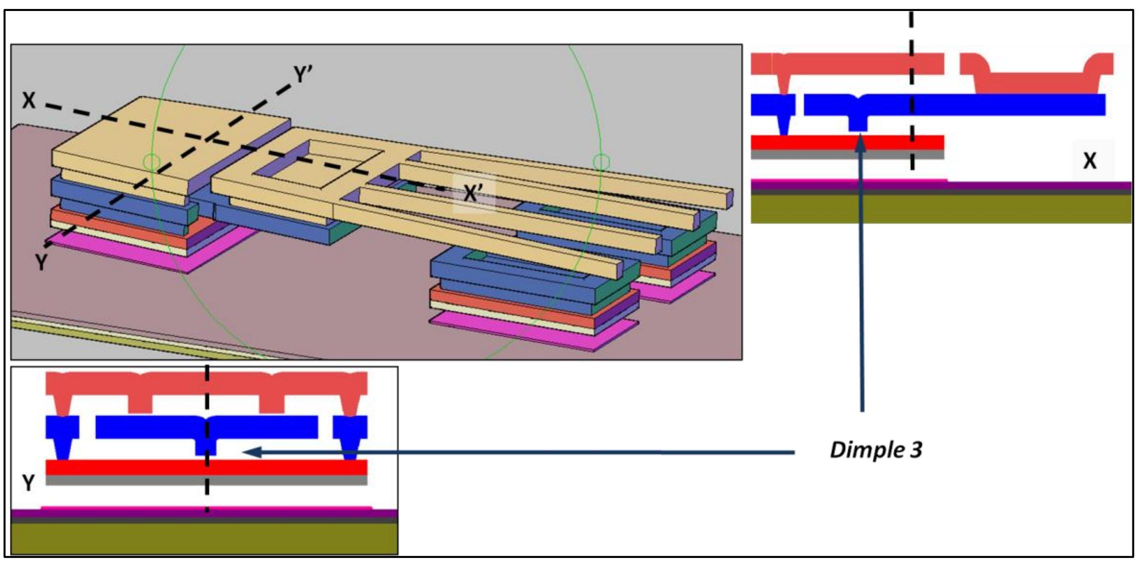


Figure 15. Isometric view of 3-D model of garage structure for resting root of Dragonfly wing

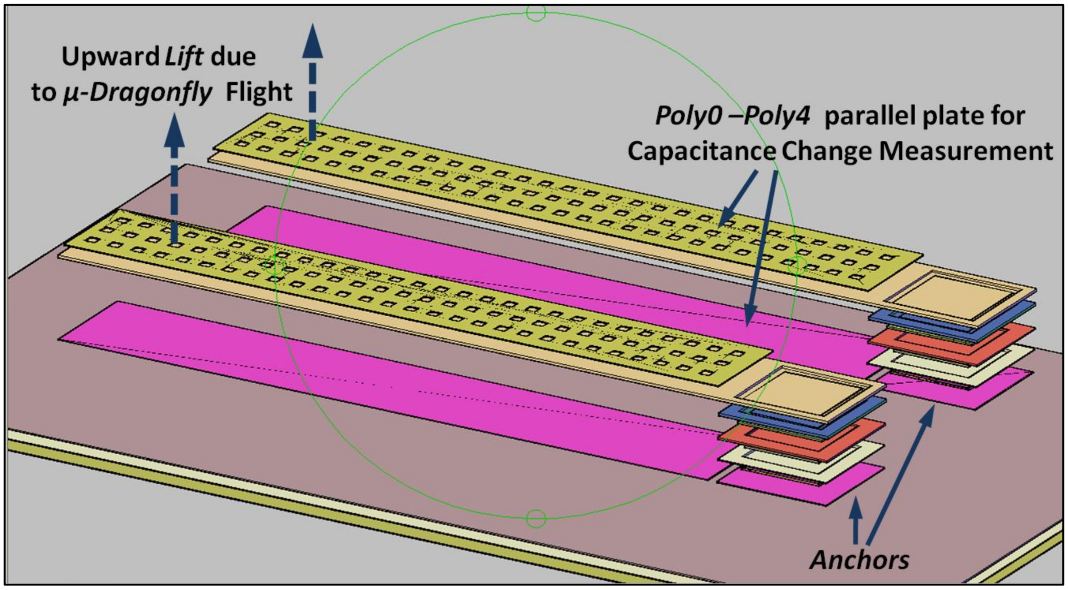


Figure 16. Exploded views of Cantilever structure supported on anchors with *Poly0* layers at the bottom

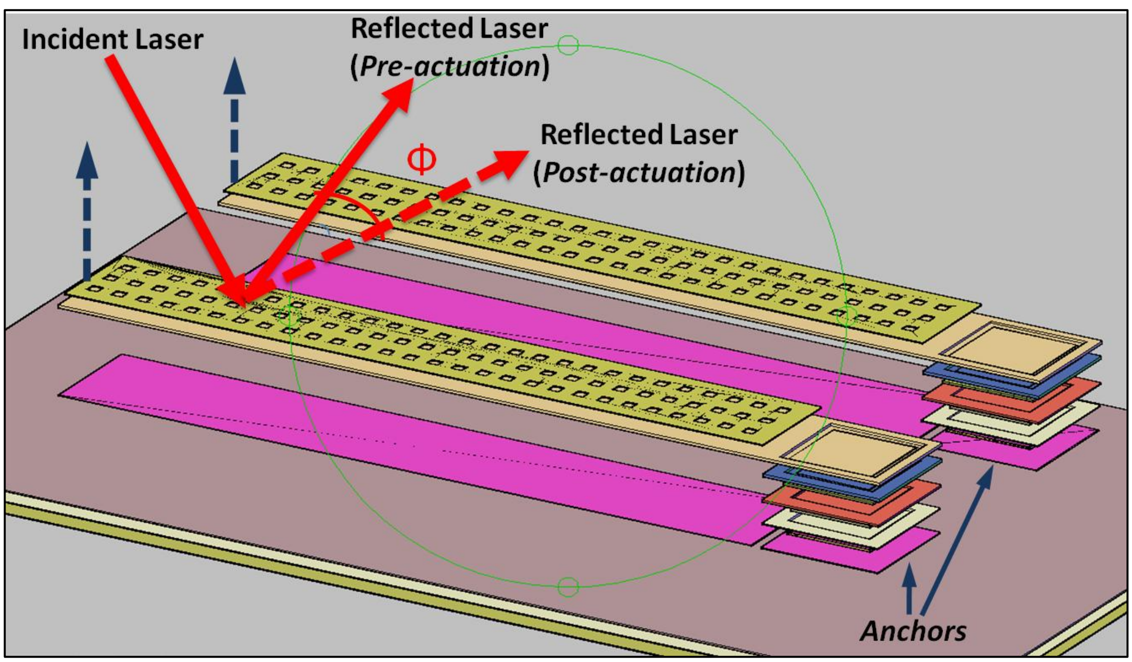


Figure 17. After lift-off the bending angle of the cantilever can be determined by change in angle of the incident laser beam

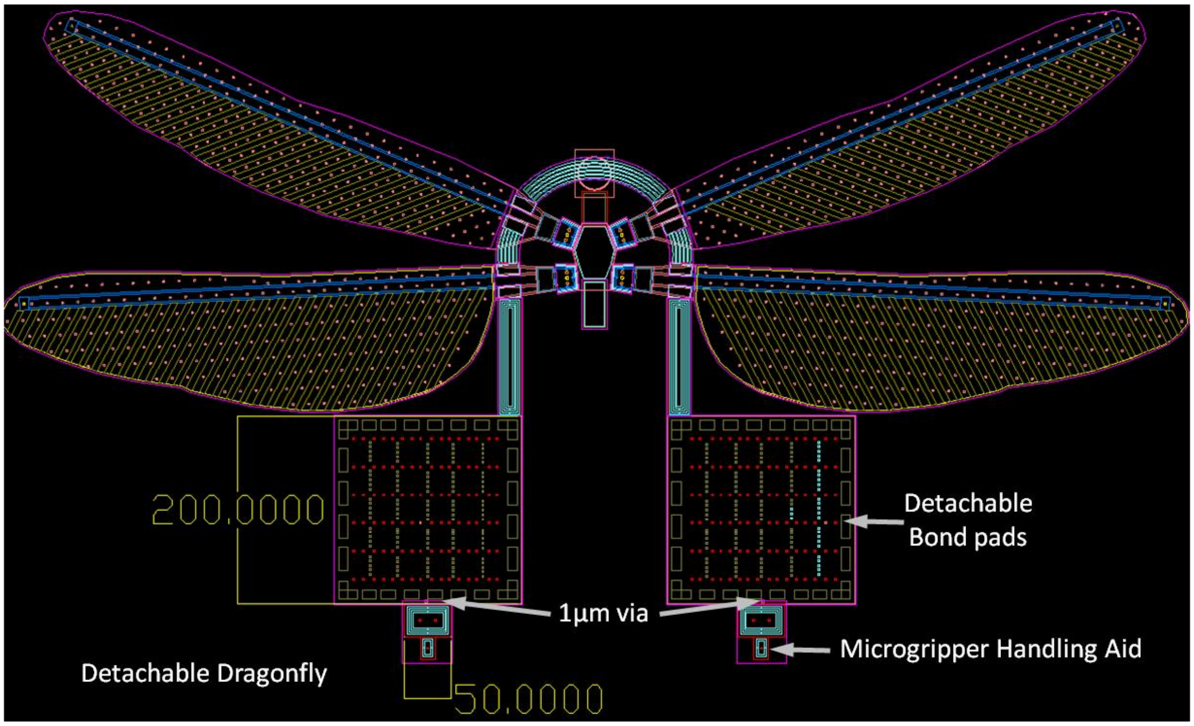


Figure 18. AutoCAD 2-D Layout of detachable Dragonfly

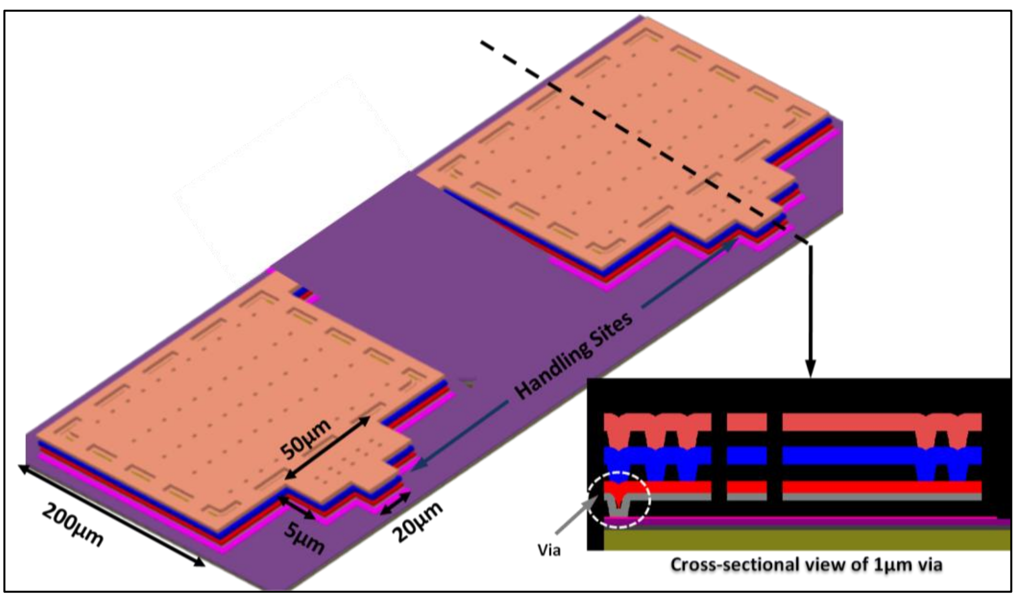


Figure 19. 3-D isometric view of detachable bondpads. Cross-section shows the 1µm via

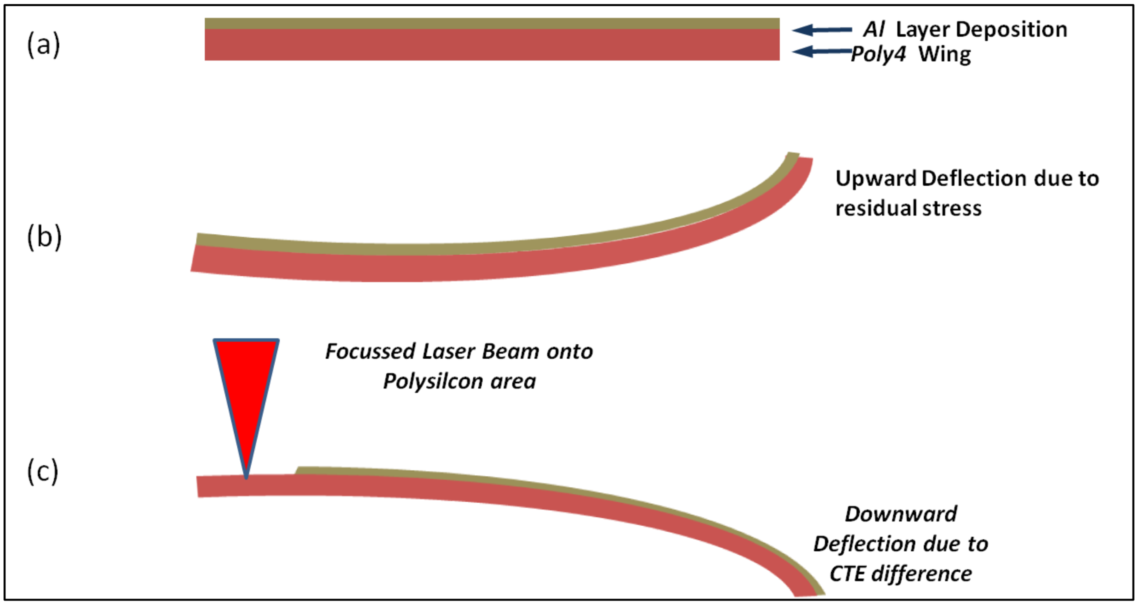


Figure 20. Opto-thermal actuation principle. a) Stacked layers during fabrication, b) upward deflection in suspended structure post-fabrication, and c) upon laser heating, the metal expands more due to high CTE to deflect downwards

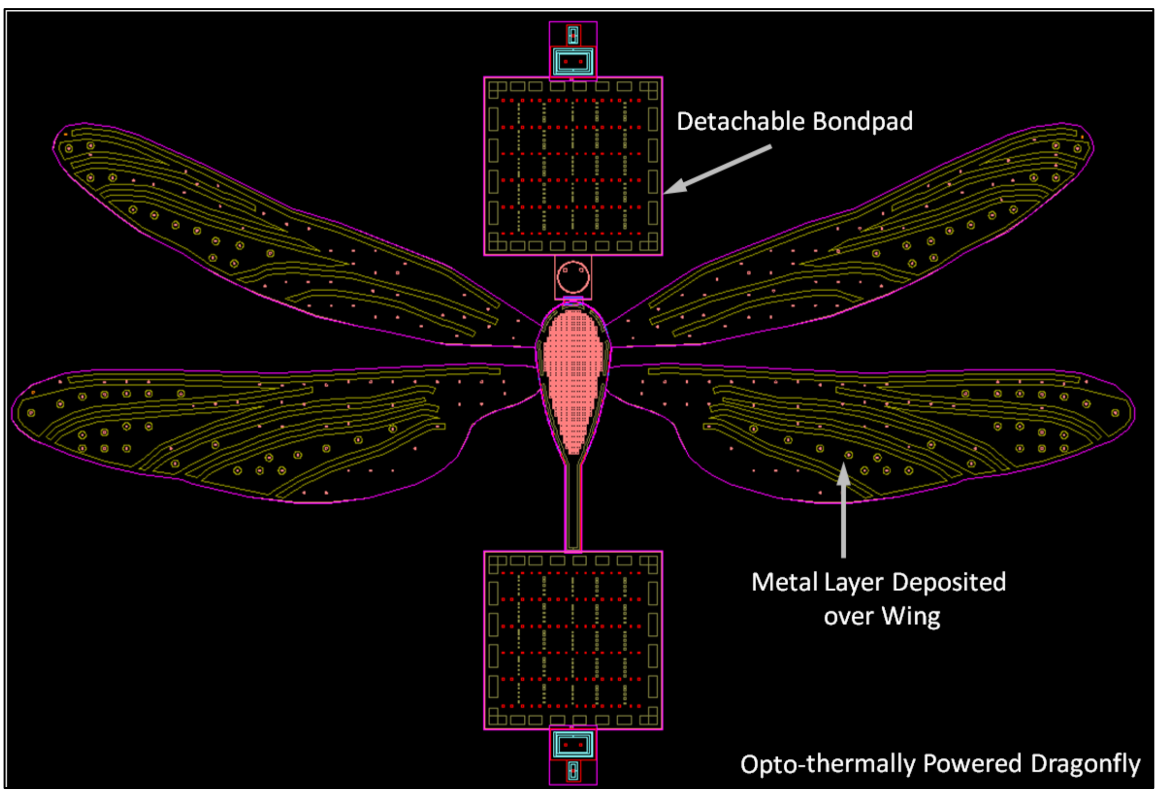


Figure 21. 2-D AutoCAD layout of opto-thermally actuated dragonfly

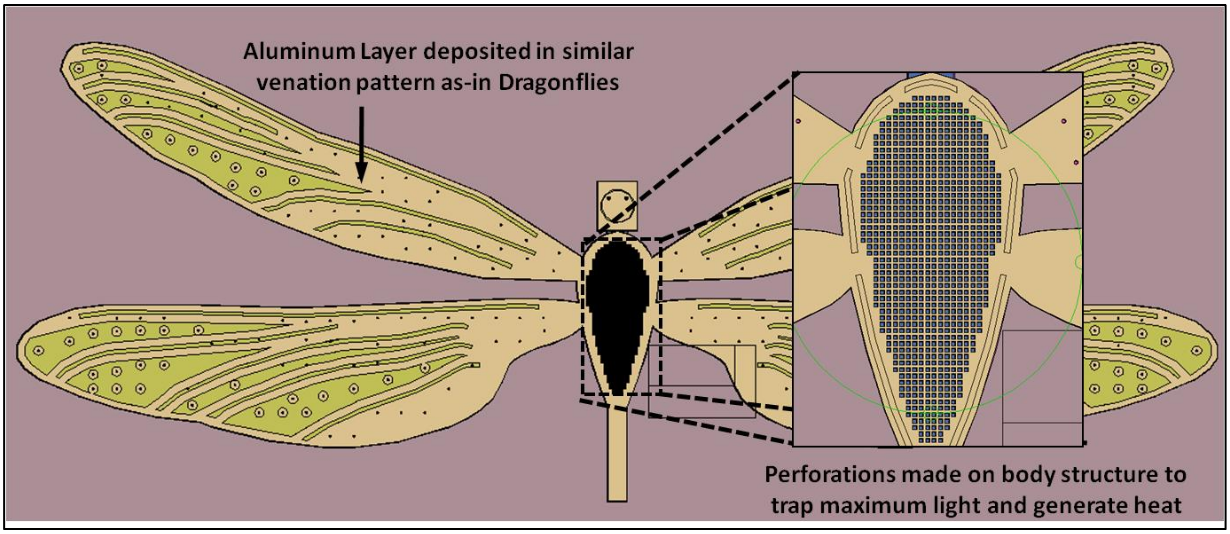


Figure 22. 3-D model of laser actuated dragonfly. Inset shows the perforations made on *Poly4* layer to trap maximum light and generate heat

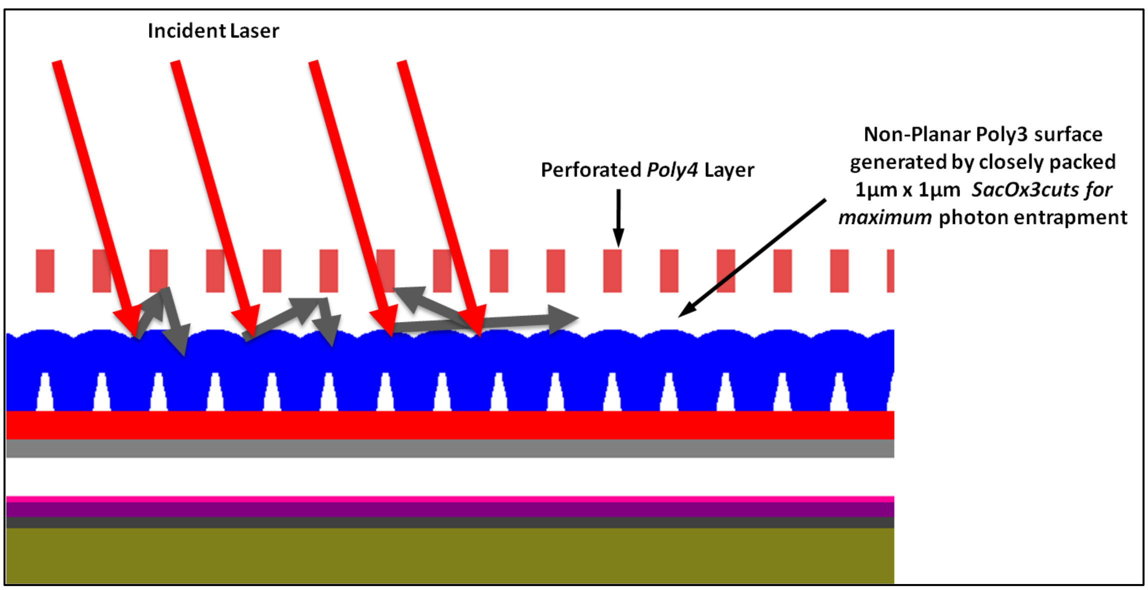


Figure 23. Cross-sectional view for light entrapment in thermally actuated dragonfly

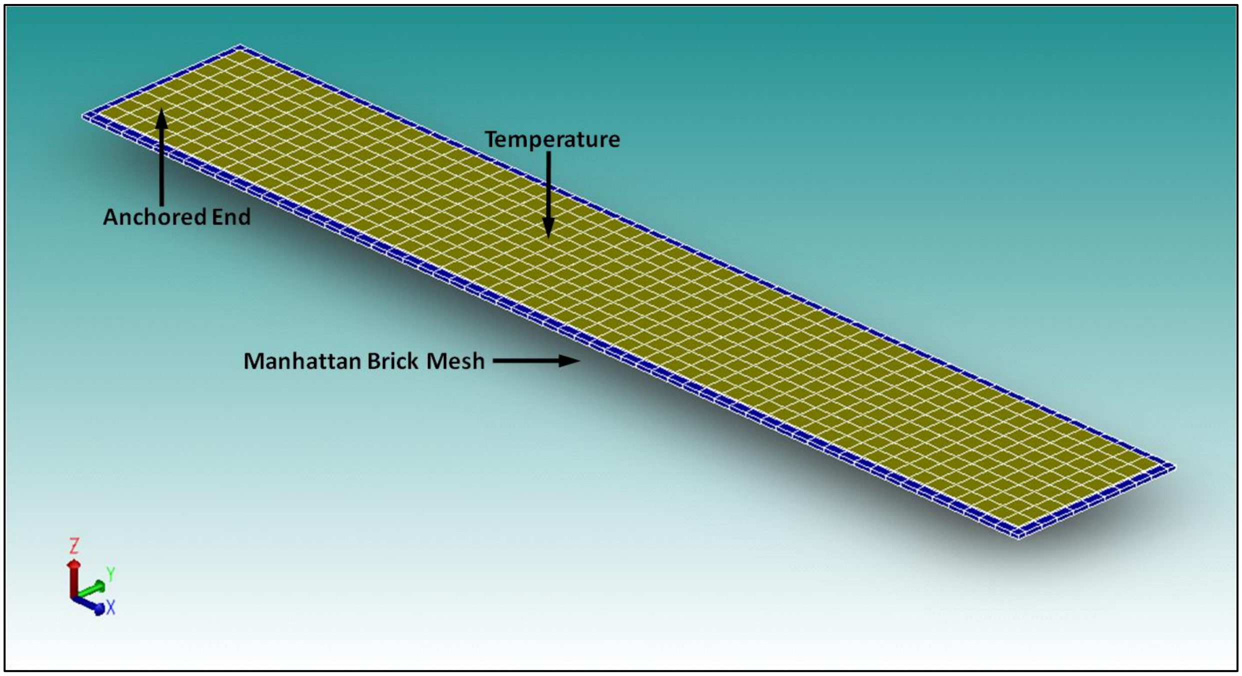


Figure 24. CoventorWare® FEA tool used for modeling the cantilever for estimate bending in wings

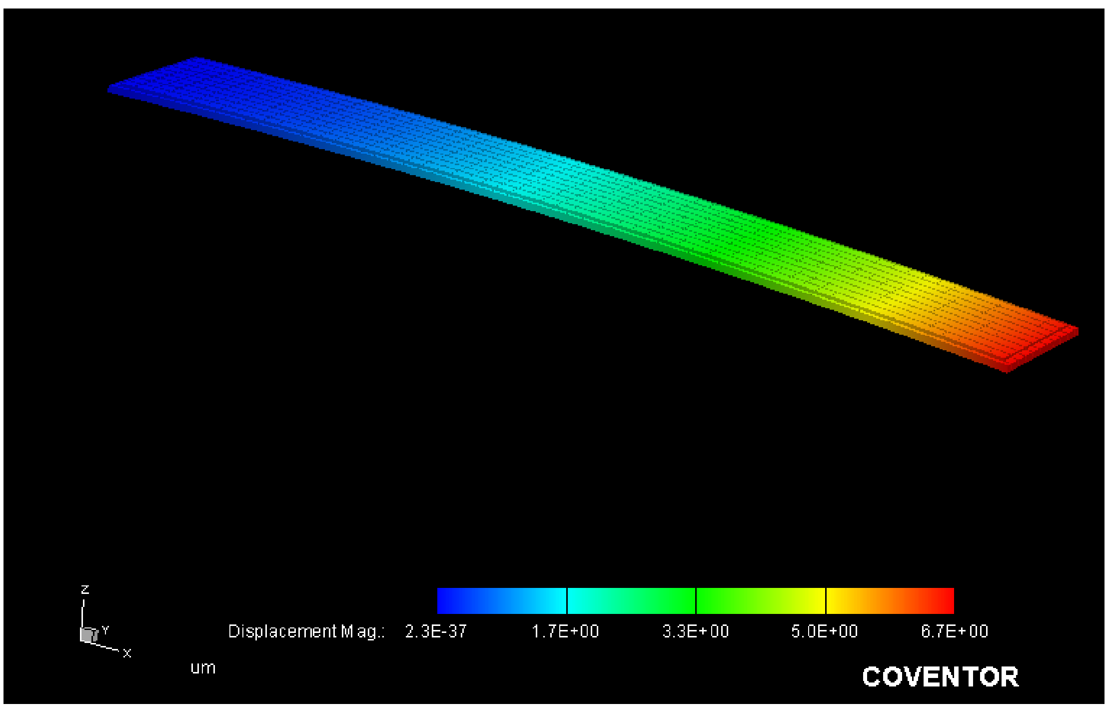


Figure 26. CoventorWare® results showing the bending of 6.7µm at 600K

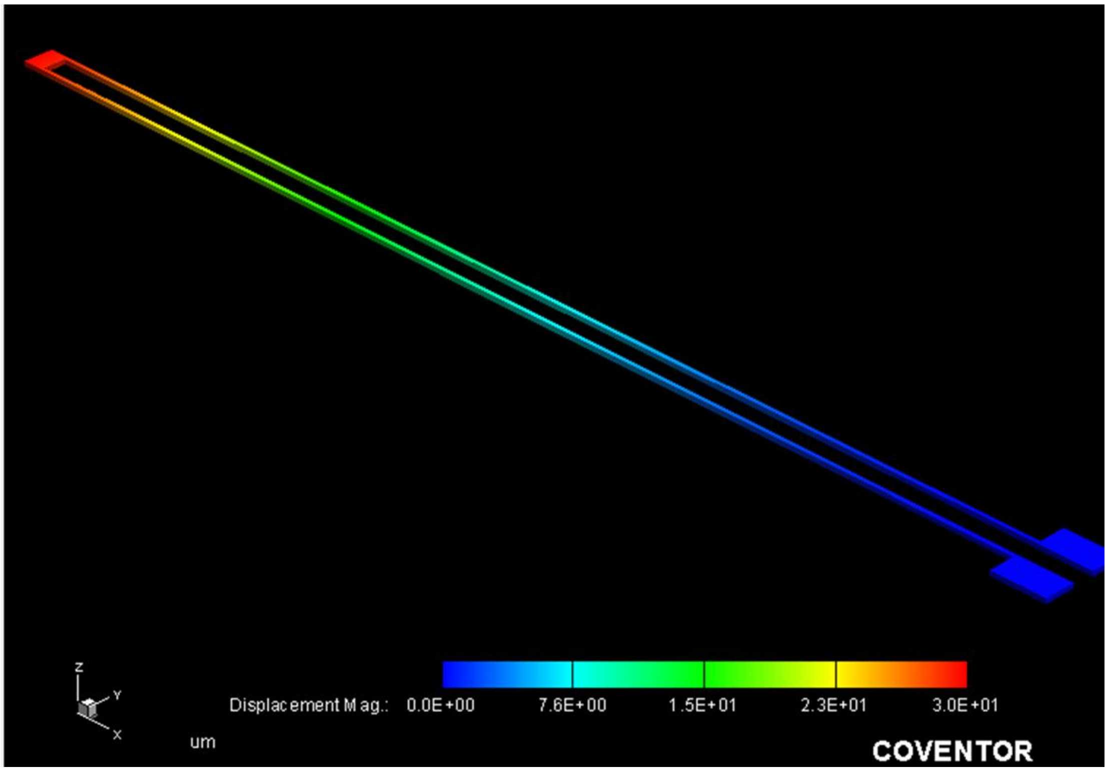


Figure 27. CoventorWare® simulation results of heater beam shows the linear expansion of 30μm at 10V

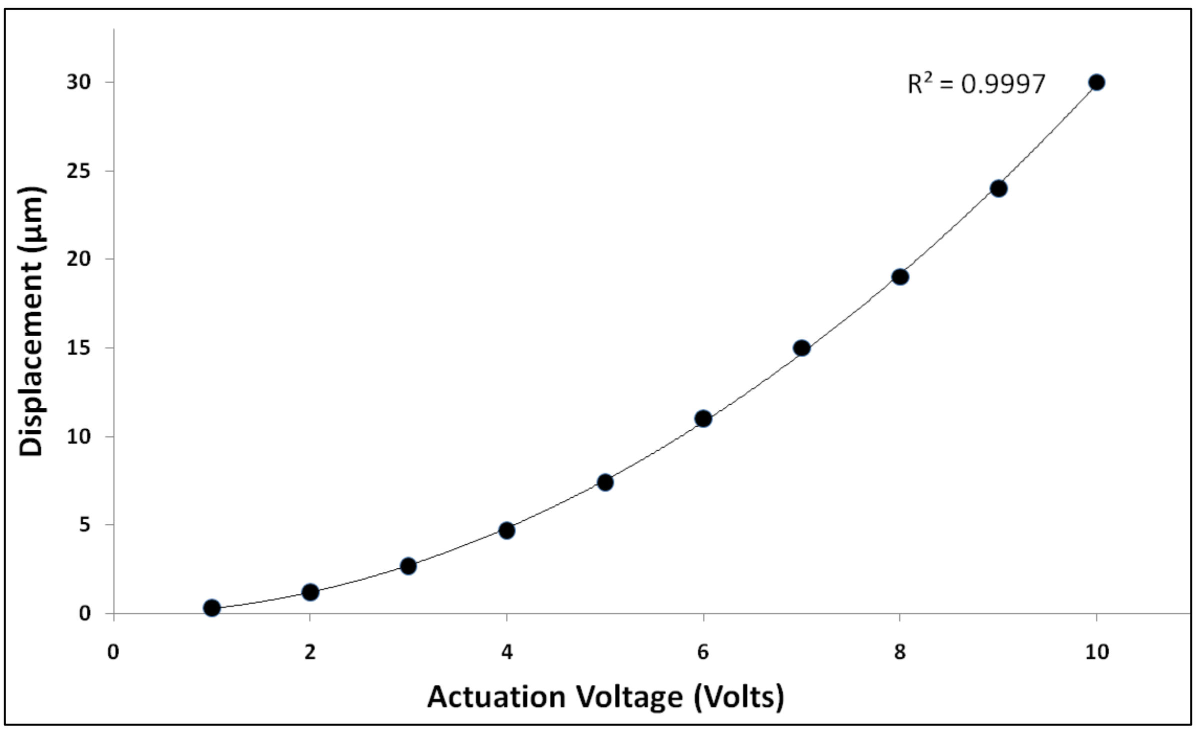


Figure 28. Plot of values obtained from FEA simulation from 1-10V fit for quadratic relationship with R-squared value of 0.99

Parameter	Forewing (TTU)	Forewing (Coleman et al.)	Back wing (TTU)	Back wing (Coleman et al.)
Deflection (µm)	30 (Simulated)	28.955	30 (Simulated)	20.139
Aspect Ratio	5.73	4.48	4.36	3.783
Drag Force (N)	3.91×10^{-13}	1.47×10^{-13}	9.98×10^{-12}	2.577×10^{-13}
Lift Force (N)	8.1×10^{-14}	2.94×10^{-14}	1.996×10^{-12}	51.5×10^{-14}
Reynolds Number	0.9917	0.00589	0.9833	0.002344

Figure 29. Table to summarize the important parameters for flight and comparison with Coleman *et al* .[5]

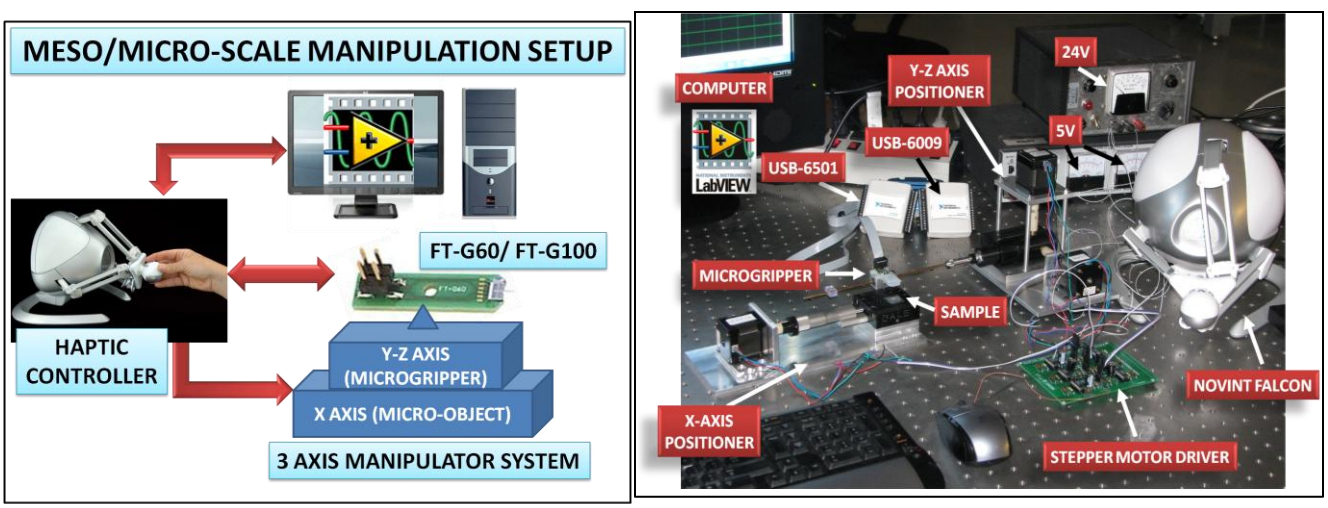


Figure 30. Meso to micro manipulation experimental setup for dragonfly handling

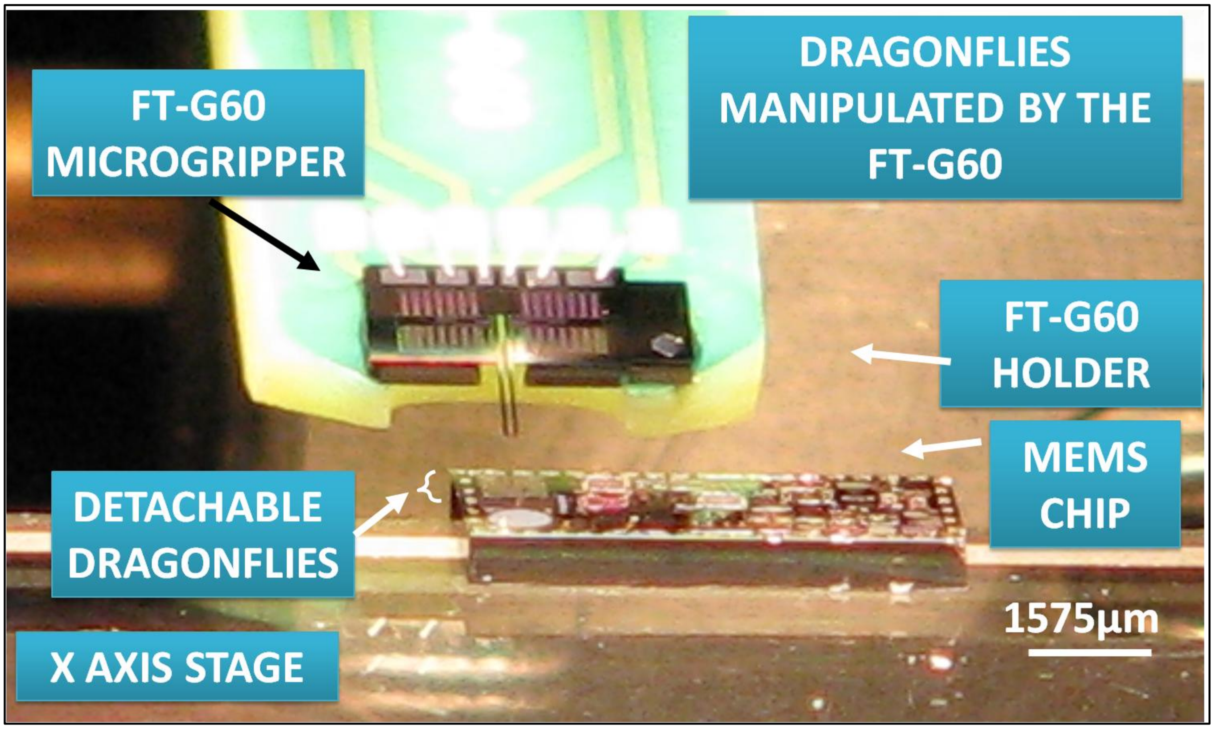


Figure 31. Proposed microgripper micro manipulation experimental setup for dragonfly handling

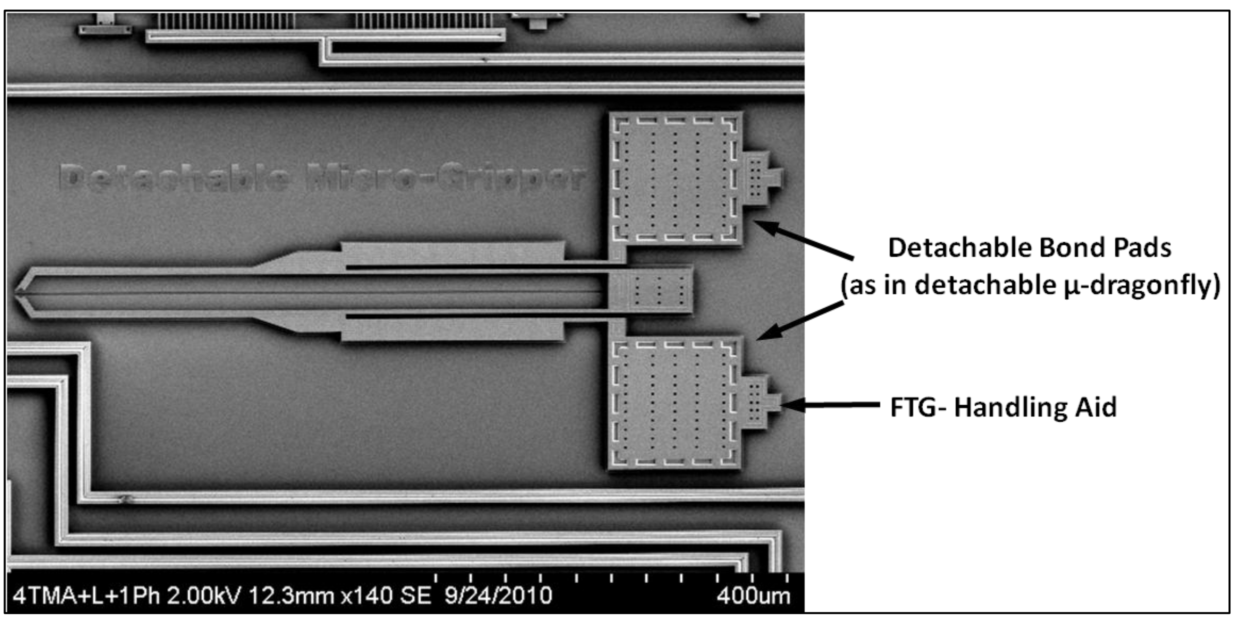


Figure 32. Detachable gripper developed by TTU

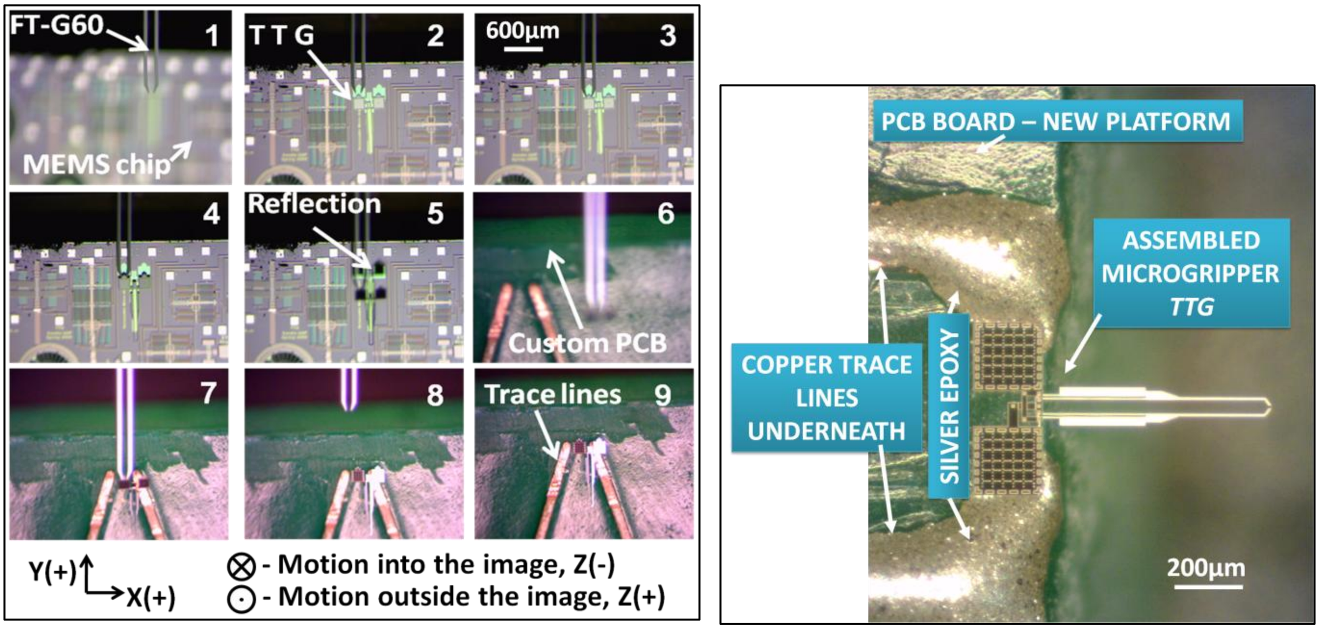


Figure 33. Sequence of Texas Tech *detachable* microgripper pick-and-place. Image on right shows the assembled microgripper on a PCB for stand-alone operation

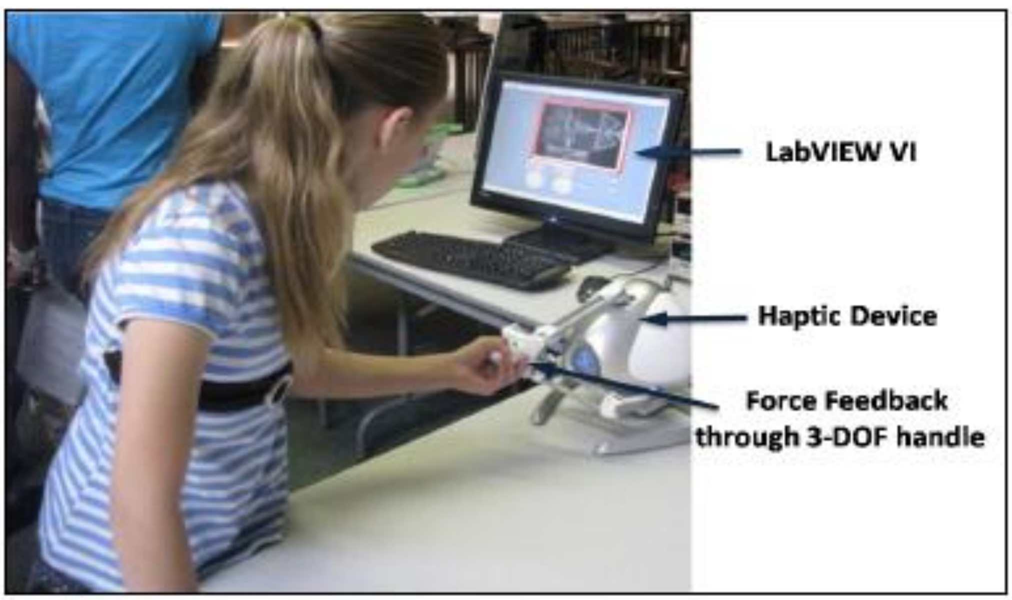


Figure 34. Elementary student actuating MEMS during Nano Day at Science Spectrum, Lubbock

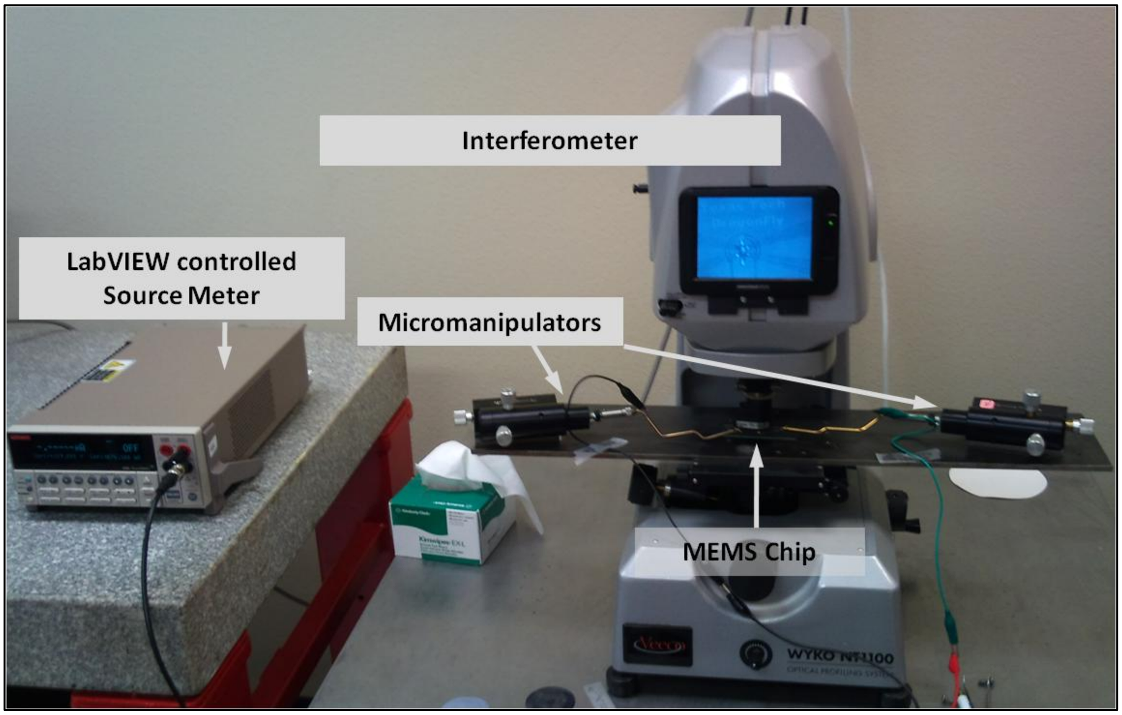


Figure 35. Interferrometric probe station for measuring wing actuation

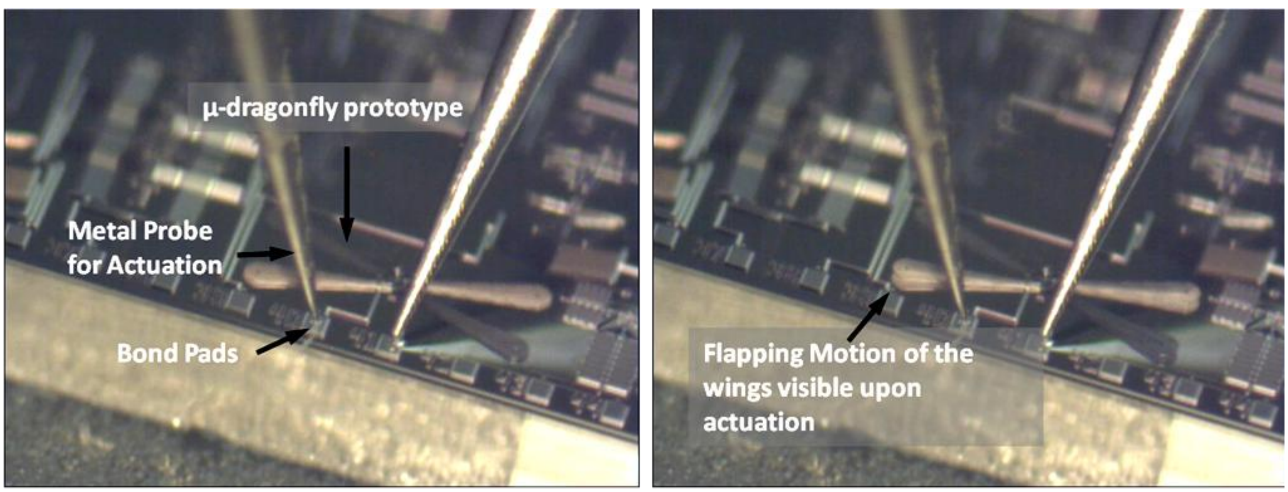


Figure 36. Actuation of µ-dragonfly prototype

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