Lowering the Resonant Frequencies of a Silicon Nitride Membrane for Measuring the Quality Factor of Deposited Optical Coatings Used in Gravitational Wave Detection

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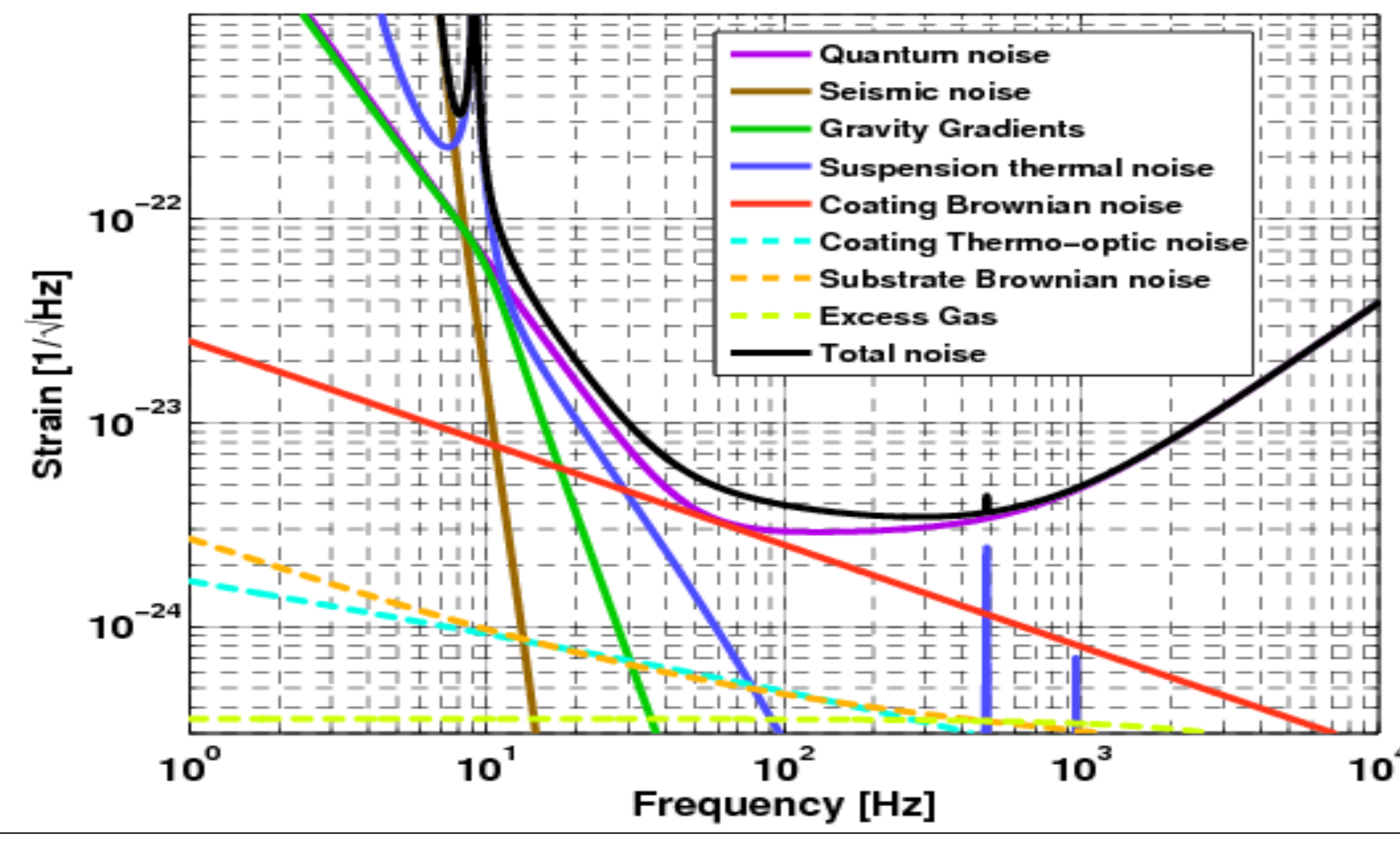
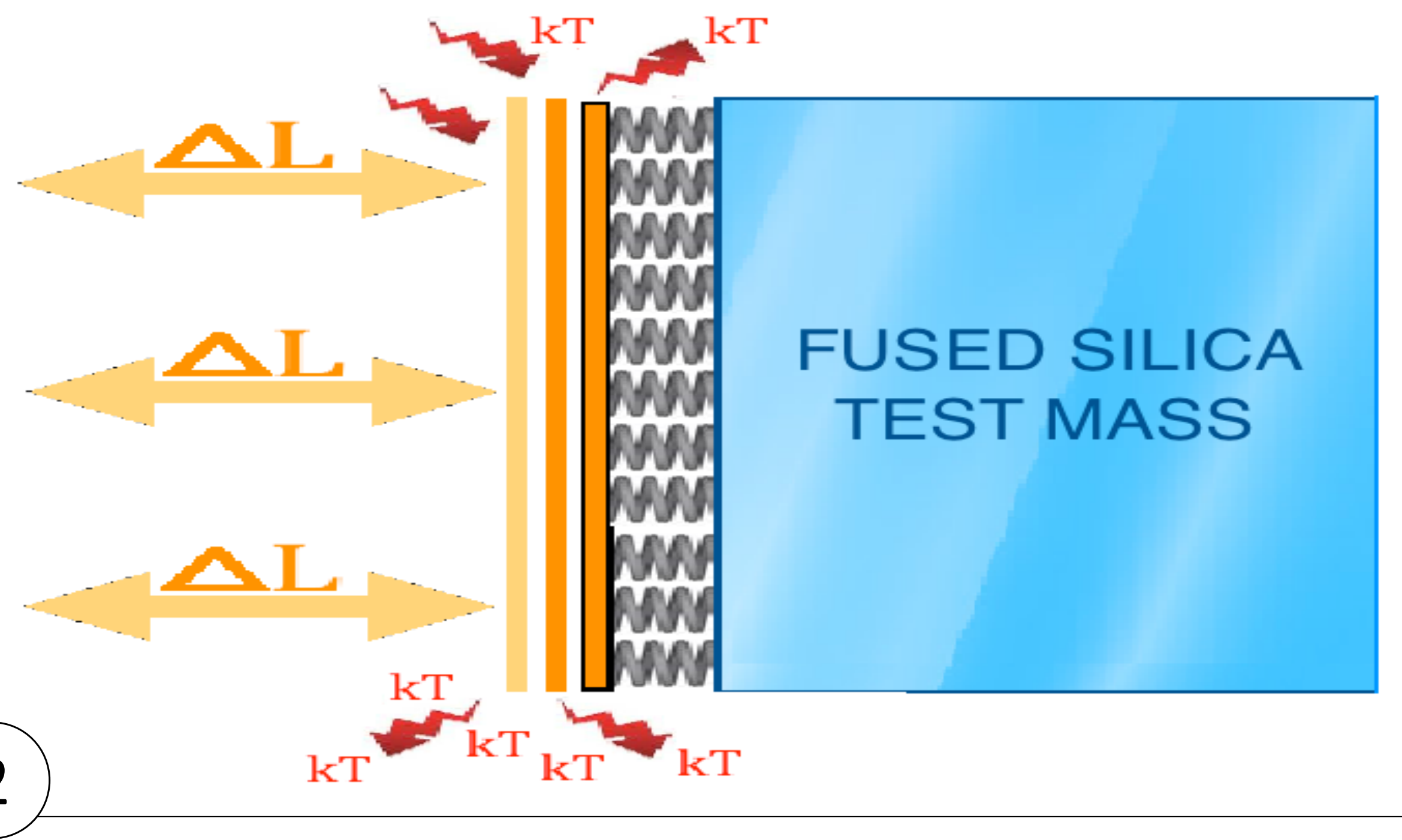


1

Coating Brownian noise is a fundamental noise in the detection of gravitational waves (GW).



2

Optical coatings on the GW detectors test masses behave as though they were attached to the substrate by springs. When random thermal energy exchanges distort them there will be an effective length change in the laser cavity.

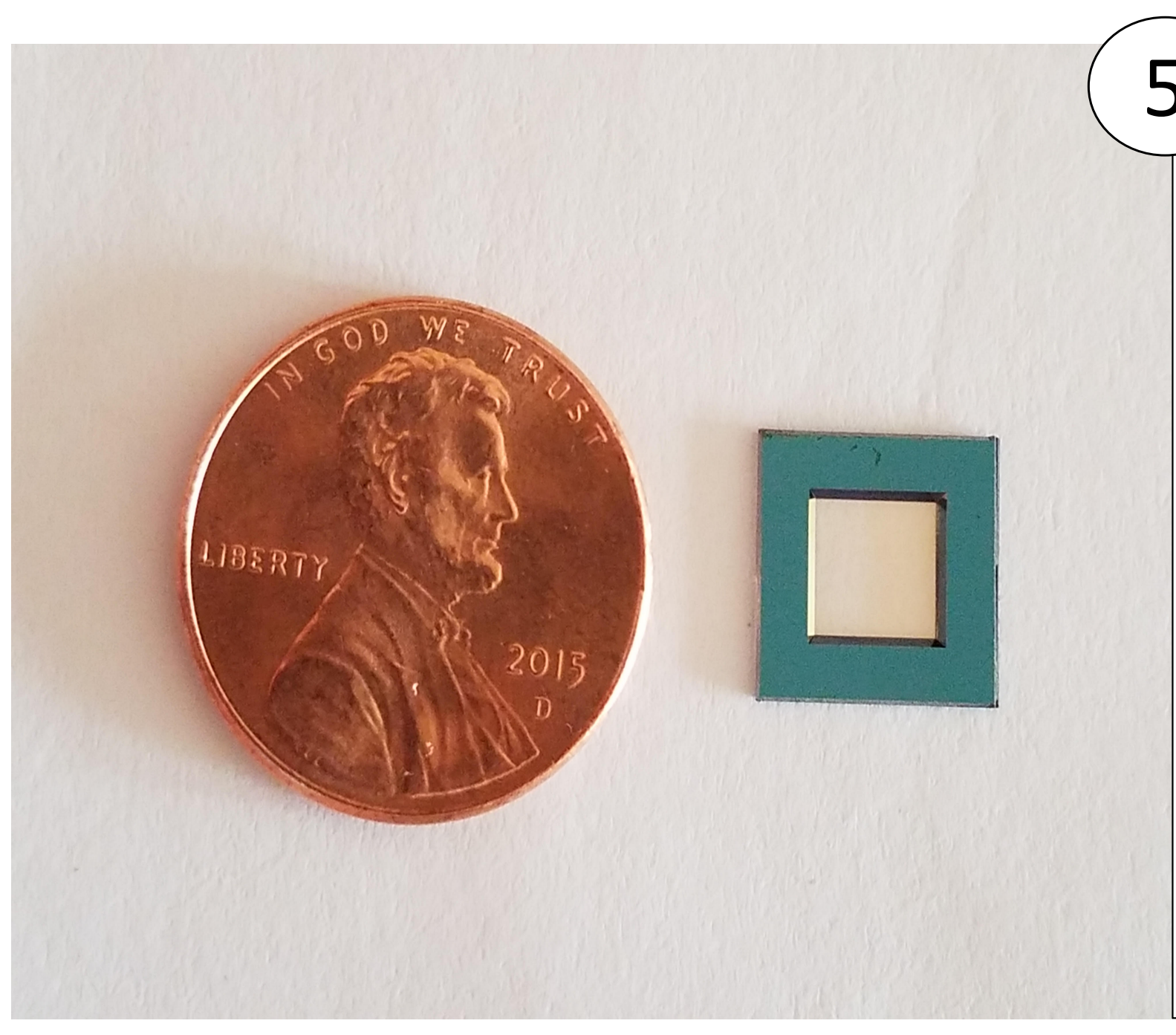
3

All materials have an intrinsic Quality Factor (Q) that describes how rapidly they randomly exchange thermal energy with the environment. A system with a high Q has low thermal noise.

$$W_{Thermal} = \frac{kT\,f}{Q}$$

4

We devised a new way to precisely measure the Q of various coating materials. The aim is to assist the development of advanced, higher Q coatings that will allow detection of GW from deeper in the Universe!



5

Silicon Nitride (SiN) membranes are a promising substrate for coatings, ideal for measuring Q of thin films. They are ~100 nm thick and have a high intrinsic Q. Elastic energy storage of resonances will be mostly in the deposited coatings.

6

The drawback to using SiN membranes as a coating substrate is their high natural resonant frequency. The first mode for a 10x10 mm framed membrane (pictured with penny) is around 134 kHz (Zwickl; et al 2008). These frequencies are outside the range for the GW detectors and data gathered from these measurements of the Q will be of limited usefulness. We need to find a way to build an oscillator operating at ~100-1000 Hz for measuring the Q of optical coatings.
Adding a mass at the center of the membrane would do the trick.

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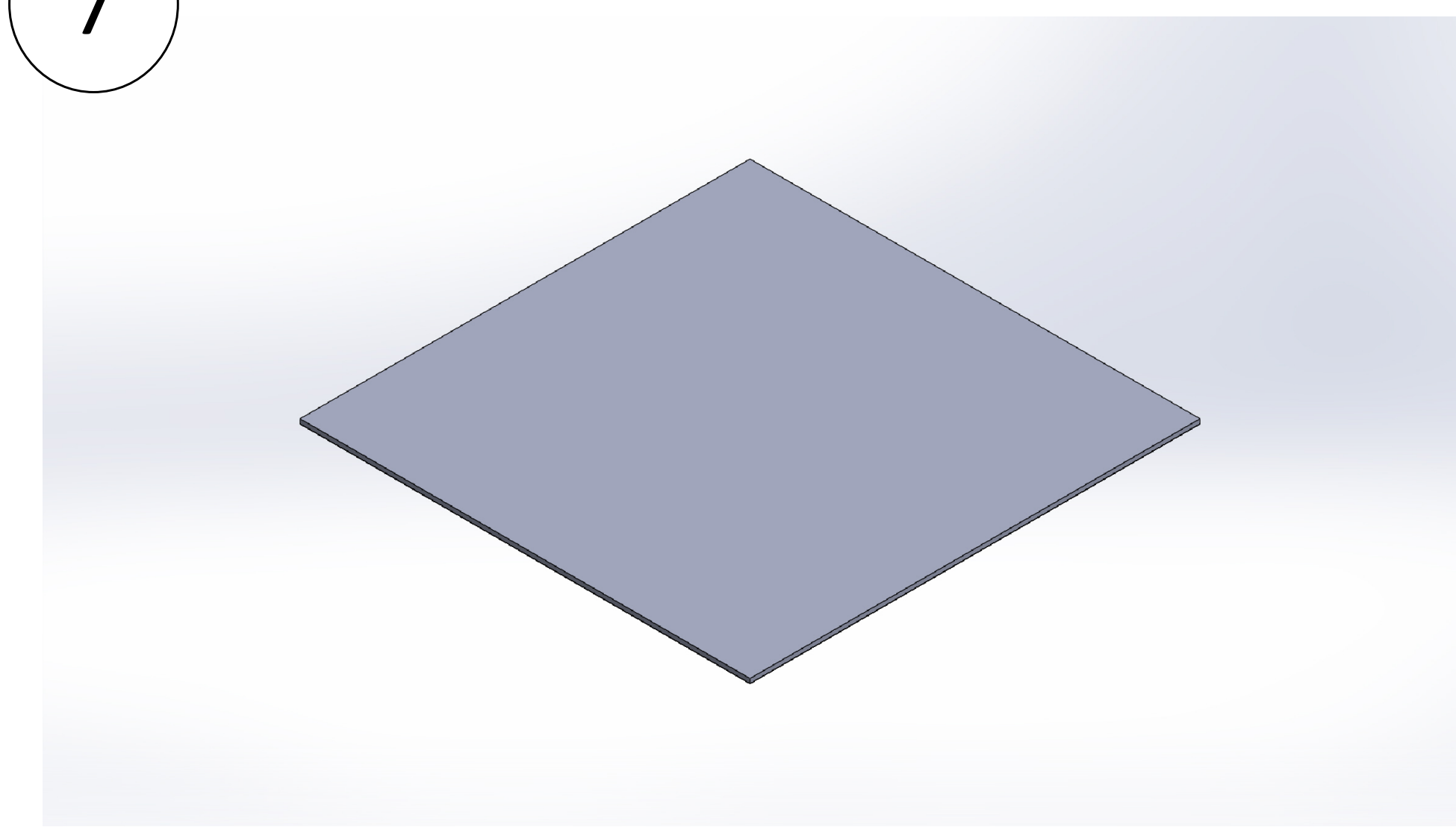
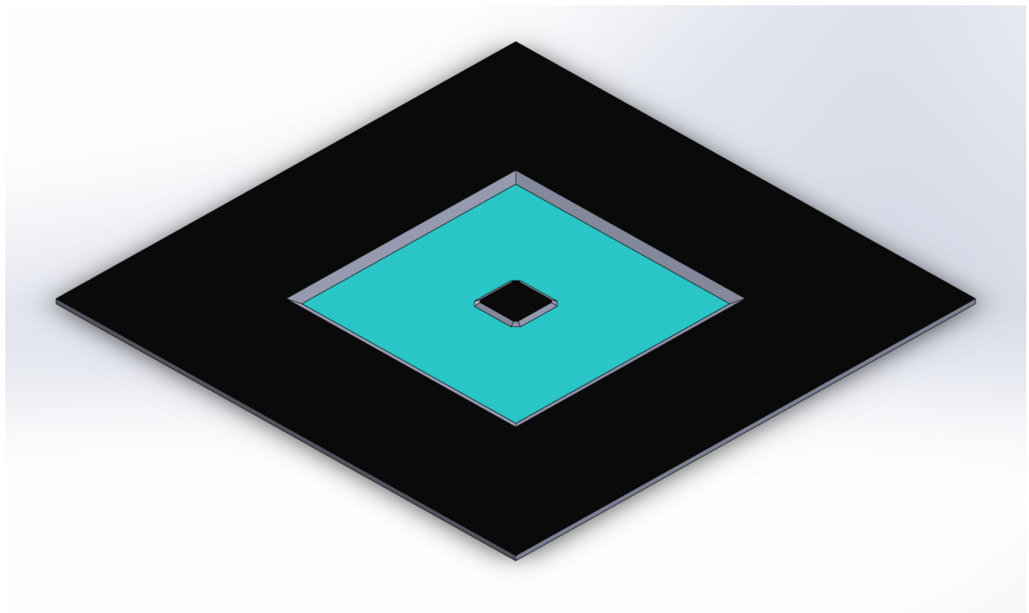
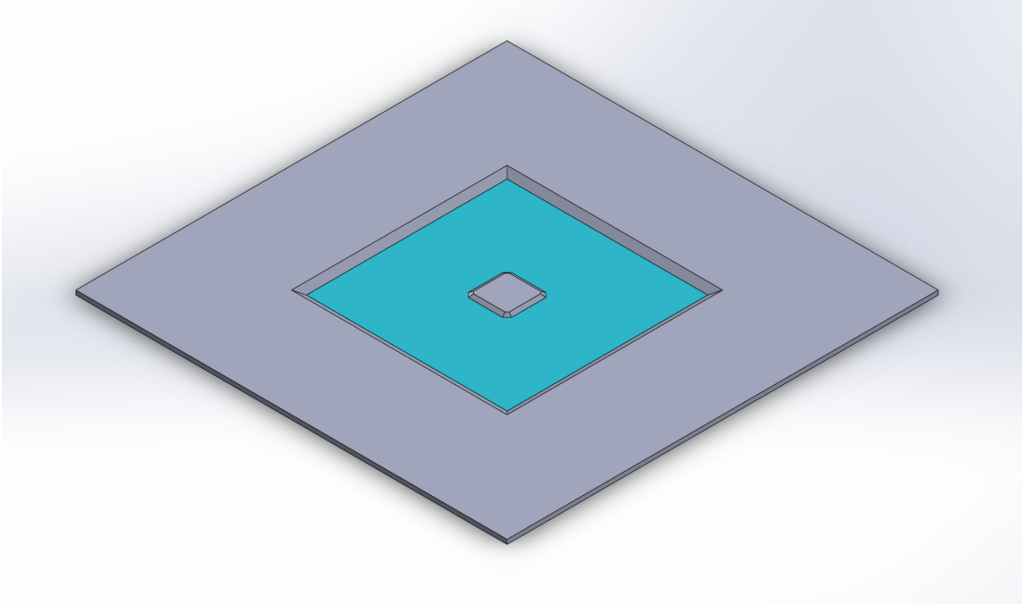


We take advantage of the manufacturing process to leave a mass of silicon in the center of the membrane. A 100 nm layer of Silicon Nitride is deposited onto the bottom face of a wafer of silicon (grey).



A masking (black) is applied to prevent frame and mass from being etched away



The etching process leaves an exposed 100 nm thick membrane with an island of Silicon in the center. The size and shape of this island mass can be altered with the masking design. SiN

8

Changing the mass effectively tunes the natural frequency of the oscillator to what is desired.

$$\omega = \sqrt{\frac{k}{m}}$$

If, for example, we want to decrease the frequency by a factor of 134 to 1 kHz a central mass of 1 mm thickness, and 10 mm sides (.27 grams) left in the center of the membrane would do so.

A typical spring constant for the membrane of approximately 10^{-1} N/m can be expected

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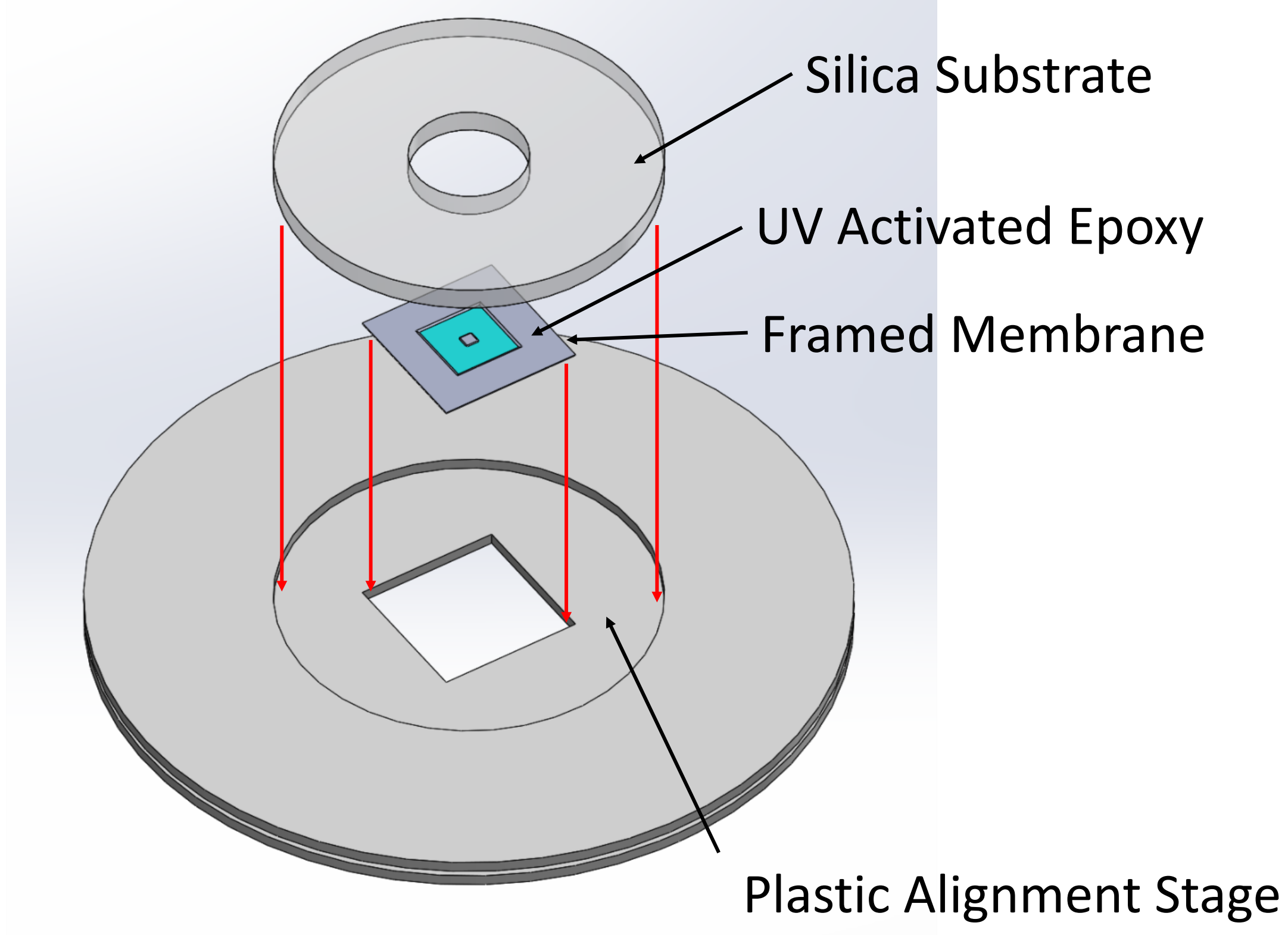
Problems arise due to recoil losses, clamping losses and handling of the system, which are solved by attaching the silicon frame to a large fused silica annular disk



A ~ 100 g ring mass would greatly reduce the recoil energy of the ~0.3 gram oscillating mass. That energy is stored, and therefore potentially lost in the support.

A potential elastic loss contributor is the glue. Assuming a contact surface of A= 250 mm^2, and a thickness of T=50 µm, we calculate the compression stiffness of the glue.

$$k = Y\frac{A}{T}$$

Y is the glue's Young's modulus (typical values vary between 2.5 and 3.5 Gpa). This gives k_{Glue} of approximately 10^{11} .

10

We made an upper limit evaluation of the recoil energy:
From the classical treatment of springs, we have

$$F = -kx, \qquad E = \frac{1}{2}kx^2$$

The stored energy in the two parts of our system are

$$E_{Stored\ in\ Membrane} = \frac{F^2}{2}10$$

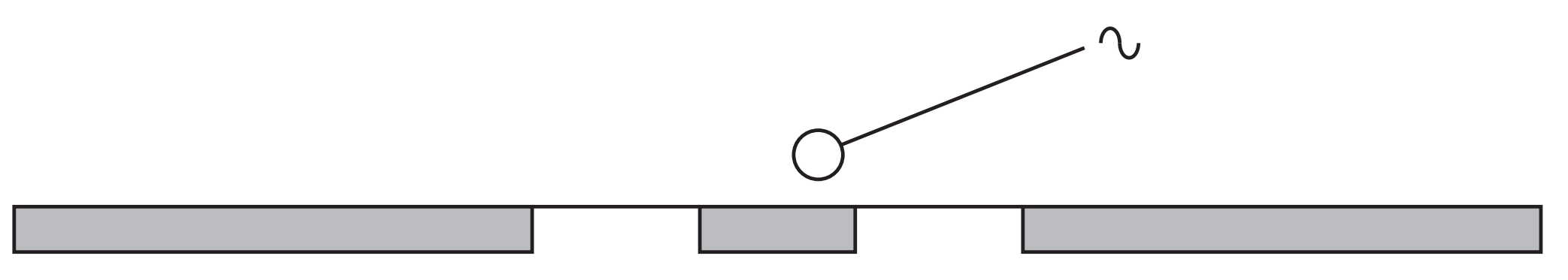
$$E_{Stored\ in\ Glue} = \frac{F^2}{2}10^{-11}$$

The ratio of the two shows us that the energy stored in the glue is negligible compared with the amount stored in the membrane.

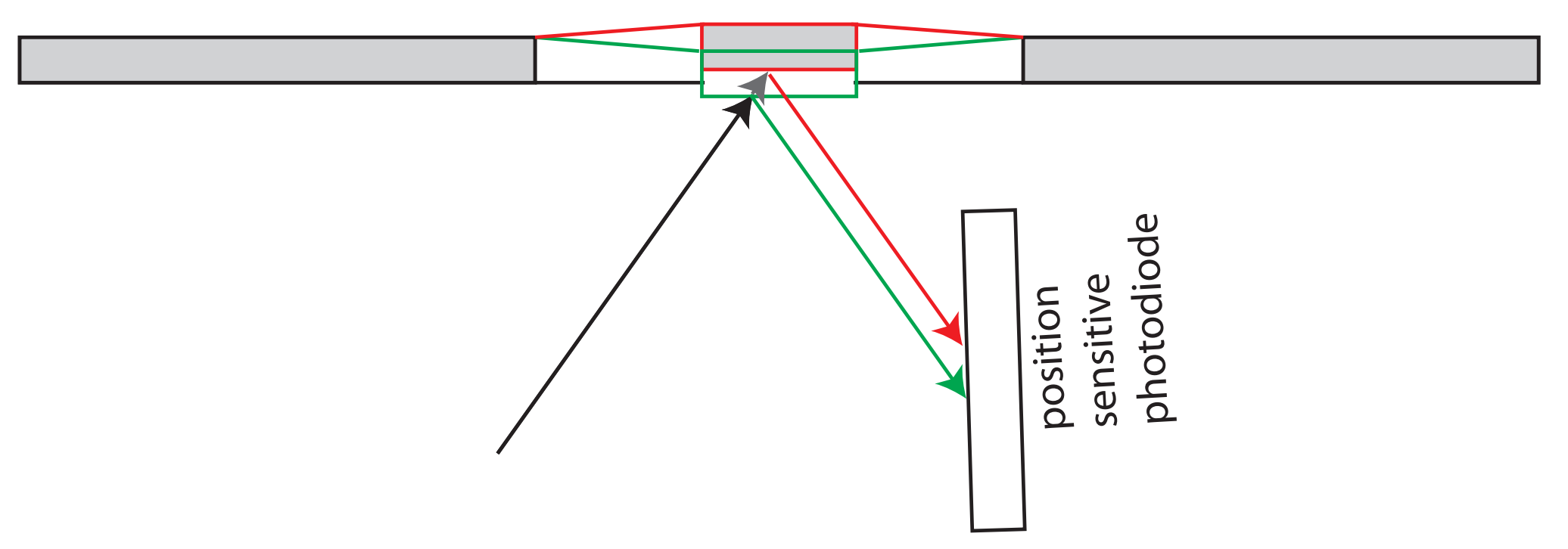
The coatings are expected to have a Q between 10^4 and 10^5. Coating will be of comparable thickness to the membrane and will be on both sides. The membrane remains in the neutral plain of bending, therefore most elastic energy is stored in the coating and direct contributions to losses from the SiN substrate is also negligible.

11

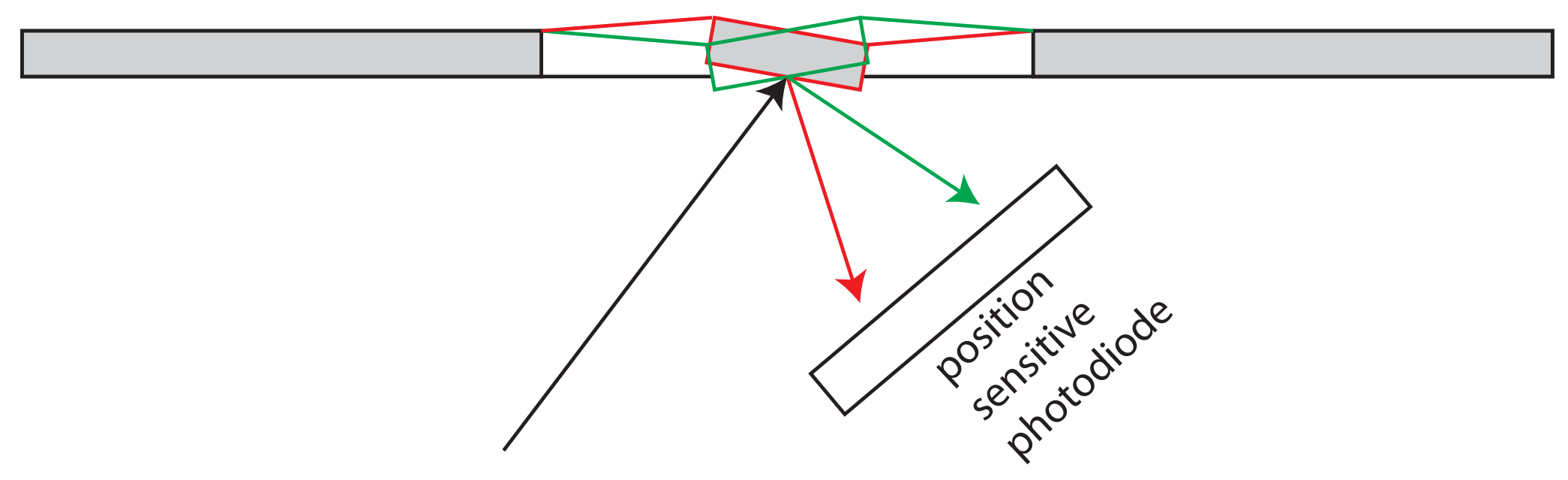
Of course, measurements must be made in ultra high vacuum. We are currently constructing our apparatus for housing the oscillator under ultra high vacuum. We will use an electrostatic actuator to excite the resonant modes of our system and an optical lever to measure the decay of its oscillations.



An electrode excites the coated membrane at the desired frequency. We place it off-center from the axis to provide the torque required for higher order modes.



First mode of resonance, and we see how the motion is measured by a laser reflected onto a position sensing photodiode.



The second resonant (tilt) mode

If successful this may become the standard for testing the Q of thin coating materials.

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