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Deformable Mirror Materials Issue Assessment

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Dr. Domenick Tenerelli
Lockheed Martin Space Systems Company (LMSSC)
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Dear Dr. Tenerelli,

It was a pleasure to speak with you and Dr. Olivier Guyon about your project to develop a coronagraph and in particular about materials science considerations in the development of the deformable mirror (DM) for the coronagraph. The coronagraph application will demand more of a DM than previous applications with regard to precision, and since the characterization and modeling tools are currently under development, you asked me to comment on materials issues that might impact the DM design and testing. I have not conducted research on this question, and my own research on modeling MEMS has not included DM systems. I am only in a position to discuss some general considerations that may help in developing a research plan for the DM system.

As I understand it, the relevant points about the DM system are as follows. The DM surface needs to be positioned to less than 1 Å RMS of the desired shape, and be stable to 0.3 Å RMS for an hour. In the ultimate application in space the stability requirements may be greater. For example, the DM shape can be set using a bright star and then allow the coronagraph to be turned to a dim star to collect data for several hours, counting on the mirror shape to be stable. The DM is made of a polysilicon membrane coated with one or more metal layers for the reflective surface and actuated by 32x32 or 64x64 electrostatic actuators on the back side. The uncertainty in the position of any one actuator should be at the few-picometer level or less averaged over the 300-µm region of the actuator. Currently, experiments are conducted that can characterize the surface shape to the 1 nm level, and it is anticipated that the experiments will be able to characterize the shape at the sub-Angstrom level but not in the immediate future. Regarding stability, under relatively large deformations (10’s of nm), the DM mirror surface shows no hysteresis at the measurable nm level.

Let me begin by saying that I am not aware of any article in the literature that directly assesses surface position stability at the sub-Angstrom level across 100’s of microns of surface. Interferometry is typically used for precise metrology over areas this large, but not typically at the sub-Angstrom level. For the purpose of these comments, I assume that it will be possible to measure the precision of the mirror shape and stability at the requisite sub-Angstrom level at some point during the coronagraph development using interferometers or some other high-precision metrology technique. The hope is that the comments at this point may identify some potential issues that can be resolved early in the development to avoid costly surprises in the later stages.

Yield phenomena. Silicon is a brittle material and exhibits little plastic flow; however, microscopic plasticity may still be relevant. As the membrane is subjected to stress due to thermal expansion, forces acting on the support structure or changes of voltage on the actuators, the local

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shear stress within the membrane changes. If the local shear stress is sufficiently high, dislocations within the membrane move, causing plastic deformation. This phenomenon is potentially relevant to the question of membrane stability because it is a thermodynamically irreversible process and causes hysteresis. The dislocation motion could occur in either the polysilicon membrane or the metallic coating, although the substantially greater thickness of the polysilicon means that it provides most of the strength of the structure. The stress needed to induce dislocation motion is set by several processes: lattice friction (the Peierls barrier), the presence of a dislocation network that impedes dislocation flow, the presence of other obstacles such as grain boundaries, inclusions, and the presence of pinning agents such as the Cottrell atmosphere of point defects. Silicon has a high Peierls barrier (estimates ranging around ~7 GPa), and the strength of polysilicon is typically high (~2 GPa with considerable variation). The Peierls barrier of typical fcc metals used for reflective coatings (e.g. Au and Al) is lower, but the film may be thin enough that only threading dislocations and interfacial dislocations are present. Since polysilicon is strong, it may be that plasticity is not important for the relatively small DM deformations needed in the coronagraph application, but an assessment of the effect of plasticity should be made.

The theory of plasticity relates the plastic strain rate to the applied shear stress. The theory of dislocations relates the plastic strain to the movement of crystal lattice defects, dislocations, and describes how the dislocations move under an applied shear stress. Both the macroscopic theory and the dislocation theory can be applied to determine how a surface moves under plastic deformation. Dislocations terminating on the surface are associated with surface steps, sub-nm scale features. Even before intersecting a surface, the elastic stress fields emanating from a dislocation can cause the displacement of a surface.

Yield phenomena can also exhibit a kind of hysteresis knows as the Bauschinger effect. The effect results from stresses built up during plastic deformation causing a tensile-compressive asymmetry in the yield surface, i.e. the stress at which dislocations move. This effect, and the other plastic deformation phenomena, is typically associated with ductile materials such as metals. They are not typically associated with brittle materials like silicon. I mention them here only because the high level of precision required for the DM application may cause sensitivity to analogous phenomena that occur very weakly in the brittle material.

Annealing. It has been suggested that the polysilicon membrane may be annealed prior to the deposition of the metal coating. Such annealing would provide the thermal energy for dislocations to flow, leading to a reduction in the residual stress and the associated dislocation network. Relaxing the residual stress may have the desired effect of reducing local stress and the associated surface deformations at the expense of spreading it across a smooth curvature of the DM, which is more easily countered with the actuators. Annealing typically reduces the yield stress of the material, although in the brittle Si this change may not be significant.

Creep. Another irreversible process of plastic flow is due to the slow relaxation of stress as a result of stress-driven point defect diffusion. This diffusion may be across grains or along grain boundaries. Creep is typically only significant at elevated temperatures or extremely long time scales.

Elastic anisotropy. Silicon is a cubic crystal in the diamond cubic crystal structure. Like other cubic crystals it has two shear moduli, C_{44} and C' (=(C_{11}-C_{12})/2). The crystal is isotropic if these moduli are equal. In silicon their ratio is C_{44}/C'=1.56. As a result, single crystal silicon is moderately anisotropic. Polycrystals with a random texture (random grain orientation) is elastically isotropic on length scales that are large compared to the grain size. Given typical stresses generated during DM operation and a knowledge of the grain structure (texture and size), it is straightforward to calculate changes in the surface morphology due to elastic anisotropy.

Anisotropic thermal expansion. Another potential cause of surface roughening is anisotropic expansion of the crystal grains even under a uniform heating. This is not an issue for silicon, gold or aluminum, since thermal expansion of cubic crystals is isotropic.

Anelasticity. A finite element model of the DM will require a constitutive model that describes the mechanics of the membrane. Such a model would necessarily include the elastic deformation of the membrane. It may also include anelastic effects and plasticity, depending on the outcome of an assessment of whether these effects are important. Anelasticity is typically described in terms of the standard linear solid, a mechanical model that includes viscous damping. There may be suitable anelastic models in the literature already.

I hope these comments are useful. I wish you well in your DM development project.

Sincerely,

Robert E. Rudd
Physicist