Multilayer Etched Antireflective Structures for Silicon Vacuum Windows

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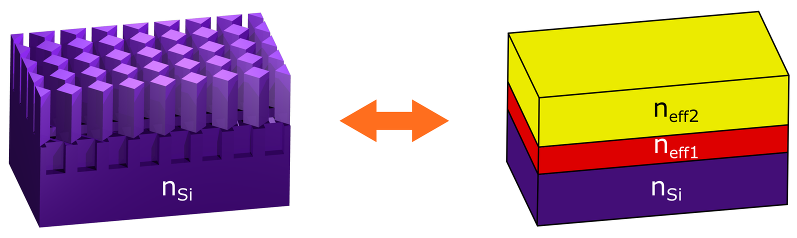
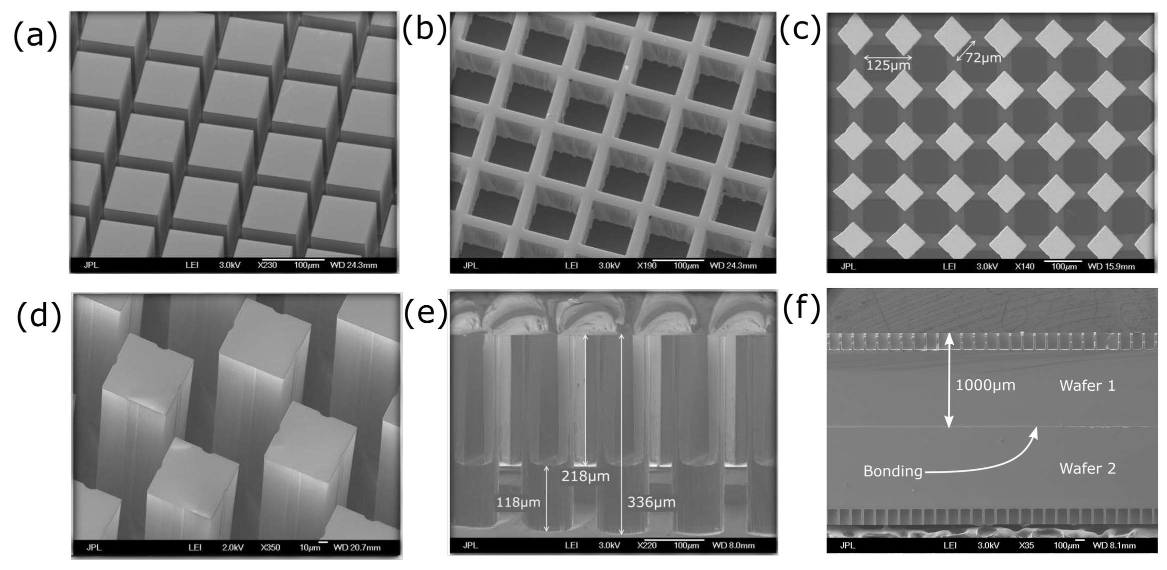
Motivation and Background

- Want vacuum windows with low absorption over broad bandwidth for (sub)millimeter astronomy missions (e.g., Sunyaev-Zel'dovich effect studies, CMB polarization, spectroscopy of high-redshift galaxies)
- Silicon is an excellent material for this purpose: has low absorption, high refractive index (= 3.42), high strength, among other advantages
- But need multi-layer antireflective coating (ARC) to mitigate reflections across a broad bandwidth; n + 1 layers required for n:1 bandwidth
- Method: etch Si substrate with sub-wavelength features to vary effective refractive index (n_{eff})
- Use deep reactive ion etching (DRIE) together with wafer bonding to build multiple layers [1]



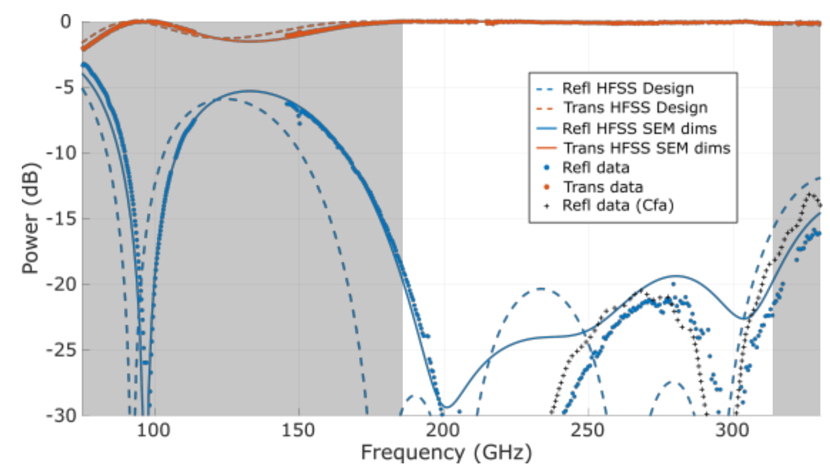
- Goal: achieve around -20 dB reflection in vacuum windows from 80 - 420 GHz
- Longer-term goal: scale to 60-300 GHz and 30-150 GHz for CMB applications

Previous Results

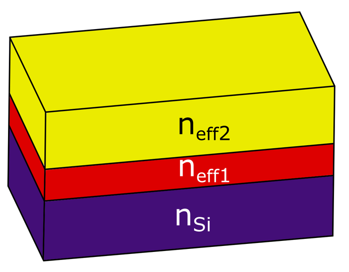


Left: scanning electron microscope images of fabricated AR structures. [2]
(a-b): single-layer AR structure
(c-e): two-layer AR structure
(f): two bonded wafers, each etched with a single AR layer at the unbonded surface

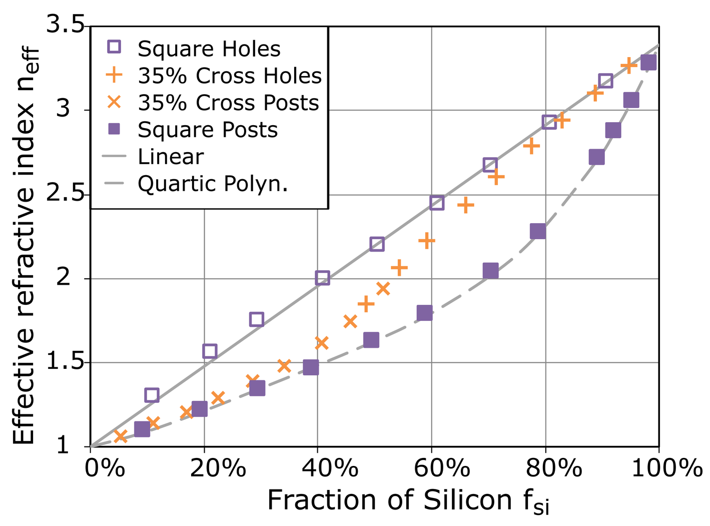
Right: reflection & transmission of an optical flat etched with a 2-layer AR structure on each side. The fabricated optic achieved <-20 dB reflection between 187 - 317 GHz. The measurements (dots: measured at 15° incidence, crosses: normal incidence) agree well with finite-element electromagnetic (HFSS) simulations of the structure adjusted for measured structure dimensions (solid lines). Dashed lines represent simulations of the original design.



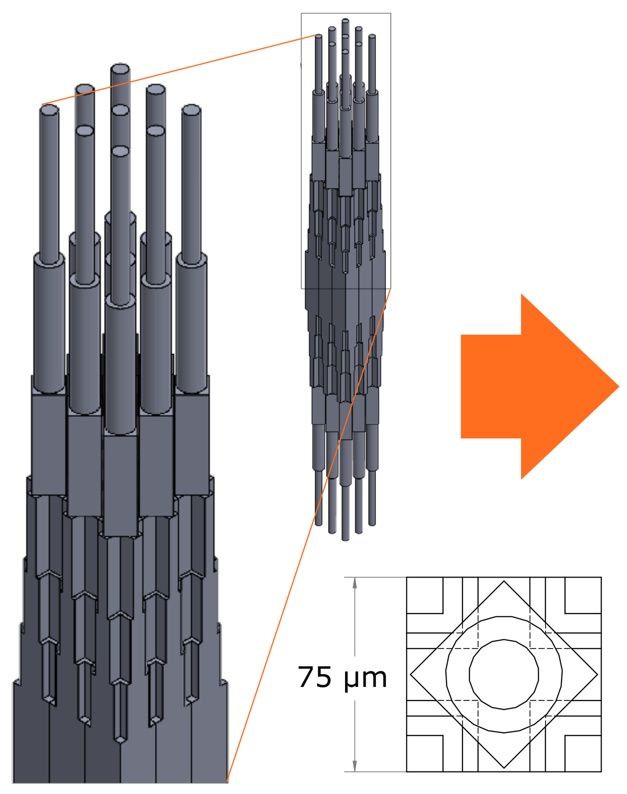
Six-Layer ARC Design and Optimization



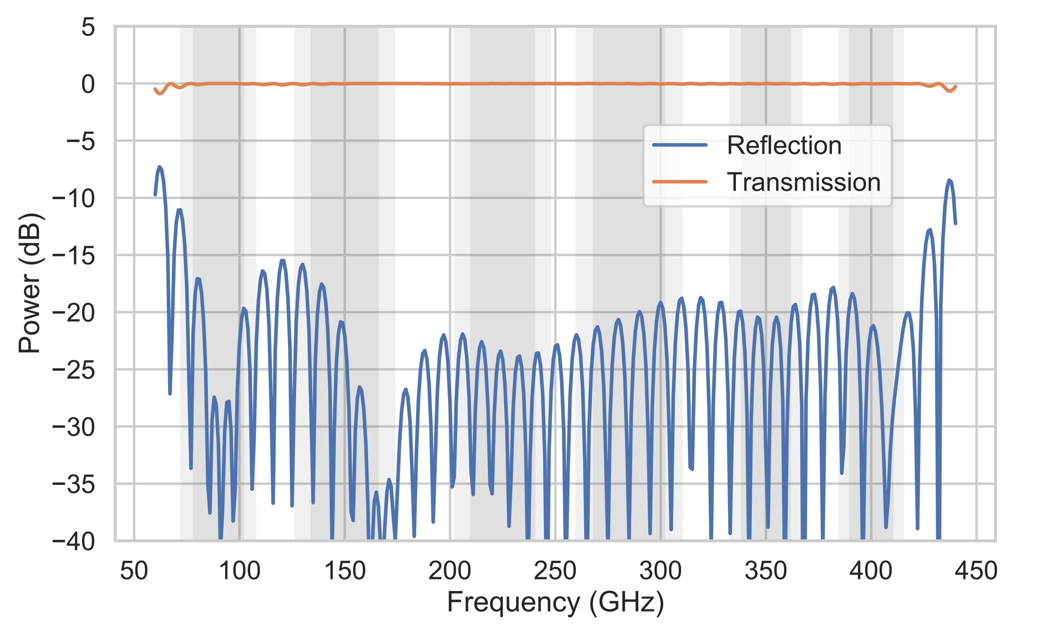
The design process begins with a slab model: every layer is assumed to be a uniform material with a single refractive index. Transformer theory allows straightforward calculation and optimization of the reflection from this structure by varying layer thicknesses and refractive indices.



The effective index of each layer is converted to a fill factor based on a polynomial fit to a lookup table precomputed with HFSS for a few different geometries (above). The choice of each layer's geometry depends on fabrication constraints, namely the minimum wall thickness (low n_{eff} ➔ use posts) and DRIE aspect ratio (high n_{eff} ➔ use holes).

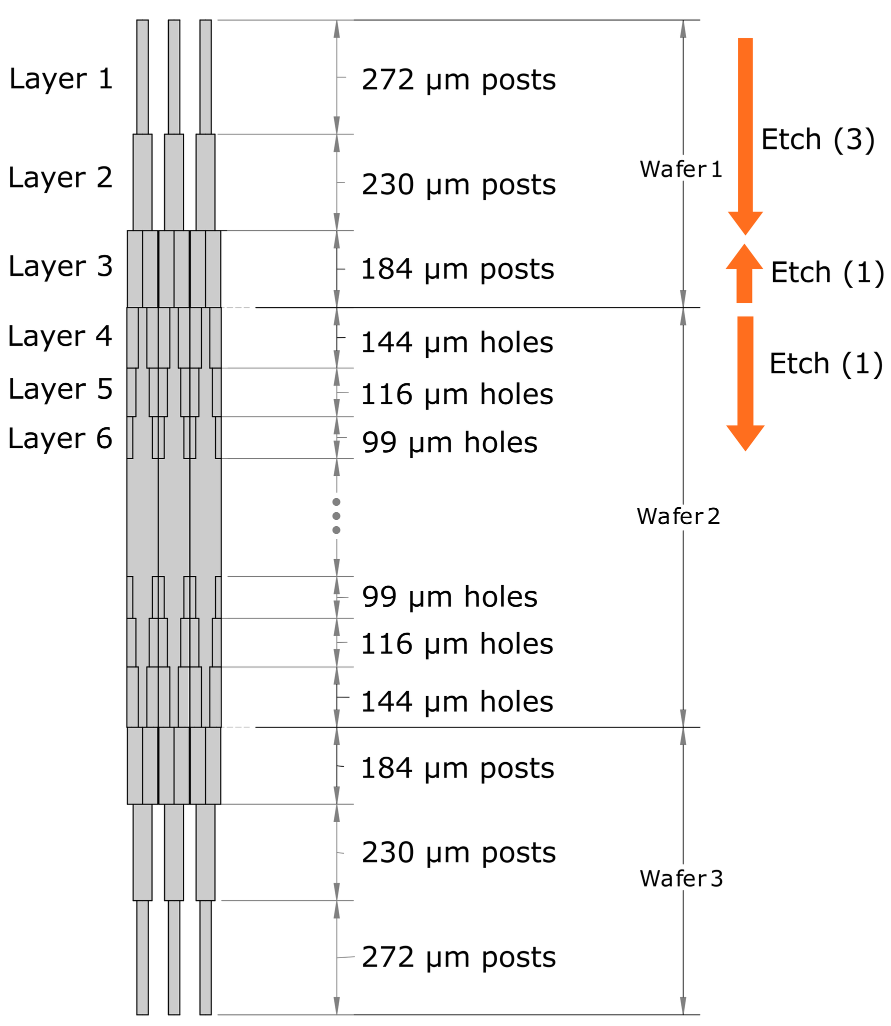


The periodic structure can now be simulated in HFSS. The simulation includes AR structures on both sides of the substrate. The 75-μm unit cell size is chosen to be small enough that chromatic effects are negligible.



Finally, the performance can be optimized by varying the dimensions in a grid search and simulating again in HFSS. The optimization considers only the reflection within the six atmospheric windows, shown above in gray, which are relevant for ground-based observations. This yields mean reflection <-20 dB in each of the six bands; simply optimizing over the whole range can worsen reflections by 3 dB in the lowest and highest bands. The Fabry-Pérot fringes are due to the 4-μm-thick substrate.

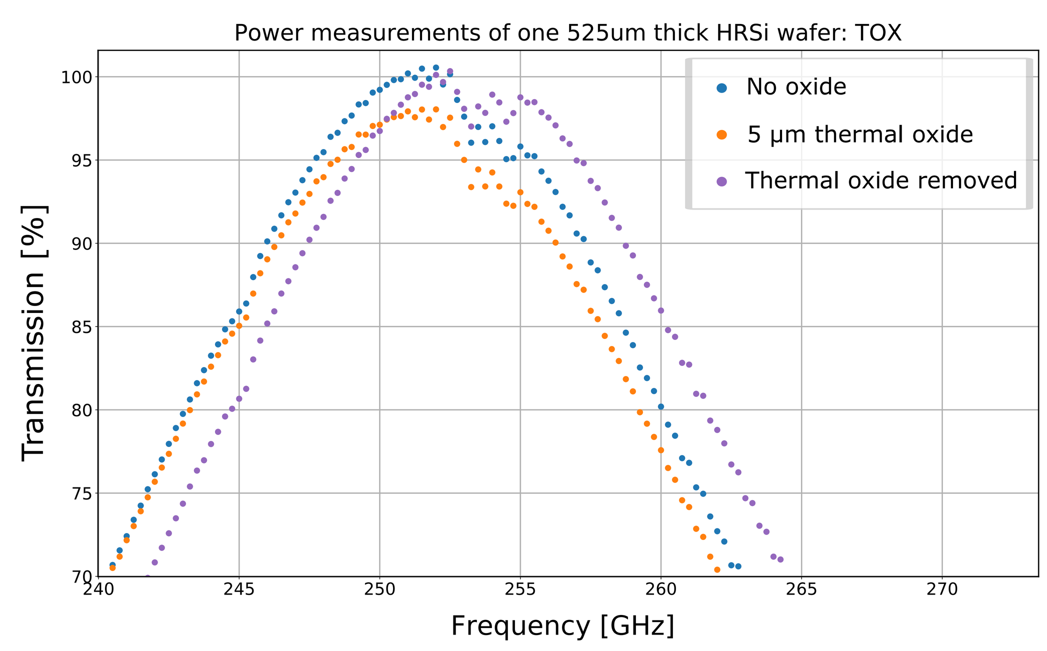
Fabrication



- Steps for six-layer design:
  1. Etch wafer 2 and inner surfaces of wafers 1 and 3 (layers 4-6 and layer 3)
  2. Bond the wafers together at the patterned surfaces (layers 3 and 4)
  3. Etch outer layers in wafers 1 and 3 (layers 1 and 2)
- Currently in the process of fabricating a four-layer structure as a simpler precursor, which has analogous etching and bonding steps

Absorption from Oxide

- Previously did a high-temperature hydrophilic wafer bonding at JPL
- Now working with a commercial vendor (Cactus Materials, Inc., AZ, USA) for better alignment (maximize bonded area at patterned faces ➔ stronger bond)
- When testing single oxidized wafers (right), found ~2-3% absorption



- Removing oxide improves transmission, but some absorption is still present. Suggests contamination of the substrate during surface activation step
- Tests of unpatterned wafers bonded by Cactus using a lower temperature bond showed even higher absorption, around 8%
- Going forward, will try to use a thin enough layer that absorption becomes tolerable. May need to switch to using a hydrophobic (no oxide) bond

References

[1] C. Jung-Kubiak et al., "A Multistep DRIE Process for Complex Terahertz Waveguide Components," IEEE Transactions on Terahertz Sci. Technol. 6, 690–695 (2016).
[2] F. Defrance et al., "A 1.6:1 Bandwidth Two-Layer Antireflection Structure for Silicon Matched to the 190-310 GHz Atmospheric Window," Applied Optics, vol. 57, no. 18, p 5196-5209, Jun. 2018

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