The Grass is Always Blacker

GaSb Grass as a Novel Antireflective Surface on IR Detectors

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GaSb Reflectivity

- Infrared detectors based on GaSb often have GaSb as their first surface
- GaSb has high index (n≈3.71), leading to a reflectivity of ~35%; photons thrown away
- To prevent this loss of light, antireflective coatings are needed and commonly used

Antireflective Coatings

- Standard approach: broadband dielectric AR coatings
- Multiple quarter wave layers to block light of different wavelengths
- But, disadvantages:
  - Coating can delaminate with frequent thermal cycling
  - Bandwidth limited; 2 octaves highest commonly available (some experimental work up to 2.6 octaves, see Willey, *Appl. Opt.*, **50**(9) 2011)
  - Angle of incidence can be limited
  - Needs to be designed for each application

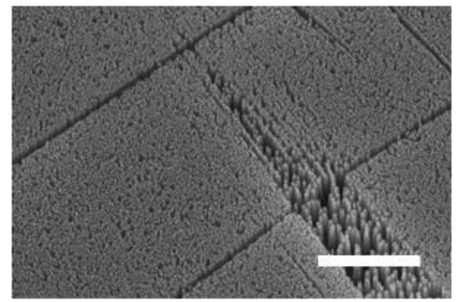
GaSb Grass

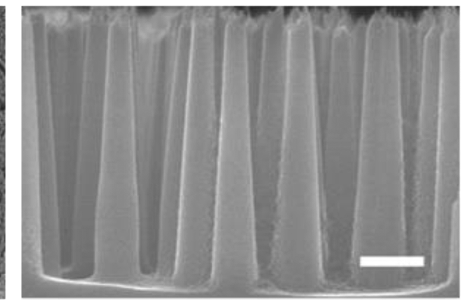
- Technique is common in the silicon world
  - Used widely on black silicon to prevent stray light reflection (e.g. author K. Yee @ JPL)
  - Used for absorption on solar cells and IR detectors (see e.g. Juntunen *et al.*, *Nat. Phot.* **10**(777), 2016)
- Has also appeared previously on GaSb
  - Cl ICP etch with O_2 micromasking (Lin *et al.*, *Nano Lett.* **15**(8), 2015), demonstrated AR to 2 μm
  - Cl ICP etch with silica colloidal array (Min *et al.*, *APL* **92**(14), 2008), demonstrated AR to 1.7 μm
  - Cl_2/SF_6 FAB etching with e-beam mask (Kanamori *et al.*, *Jpn. J. Appl. Phys.* **42**, 2003), demonstrated AR to 2.3 μm

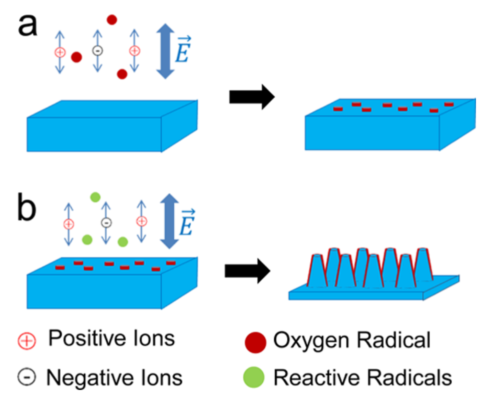
GaSb grass *(cont.)*

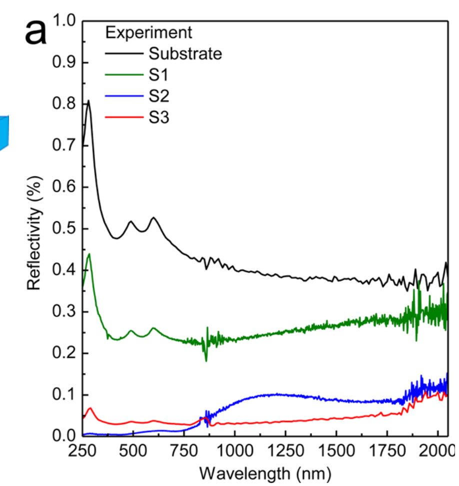
Lin *et al.*, *Nano Lett.* **15**(8), 2015:

- Etch with BCl_3/O_2 or Cl_2/O_2
- O_2 creates random micromasking blocking etch
- Grows up nanopillars or “grass” that block reflection of light
- GaSb is visibly “black” (but above bandgap, transmissive)





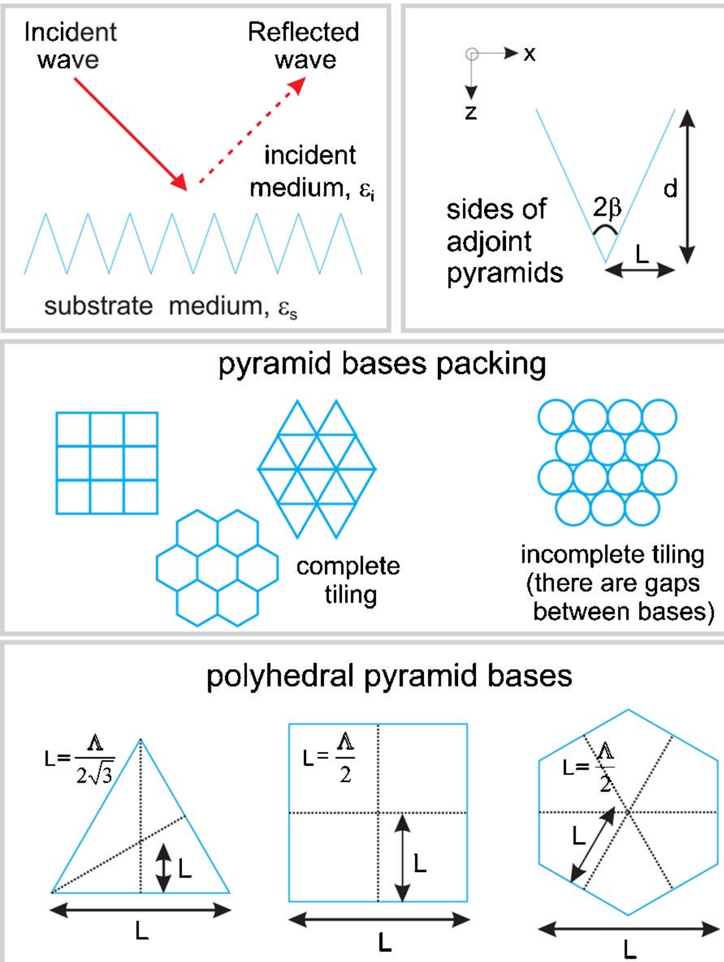




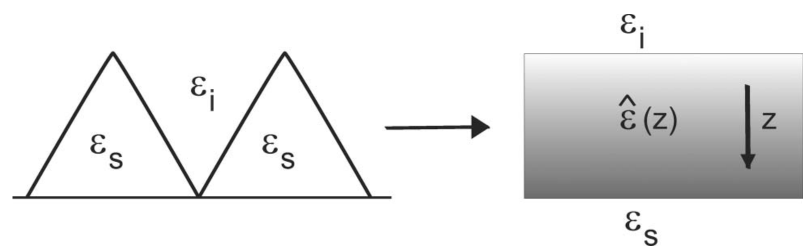
Lin *et al.*, *Nano Lett.* **15**(8), 2015

Theory

(from Deinega *et al.*, *JOSA A* **28**(5), 2011)



- Long λ limit (λ≫L):



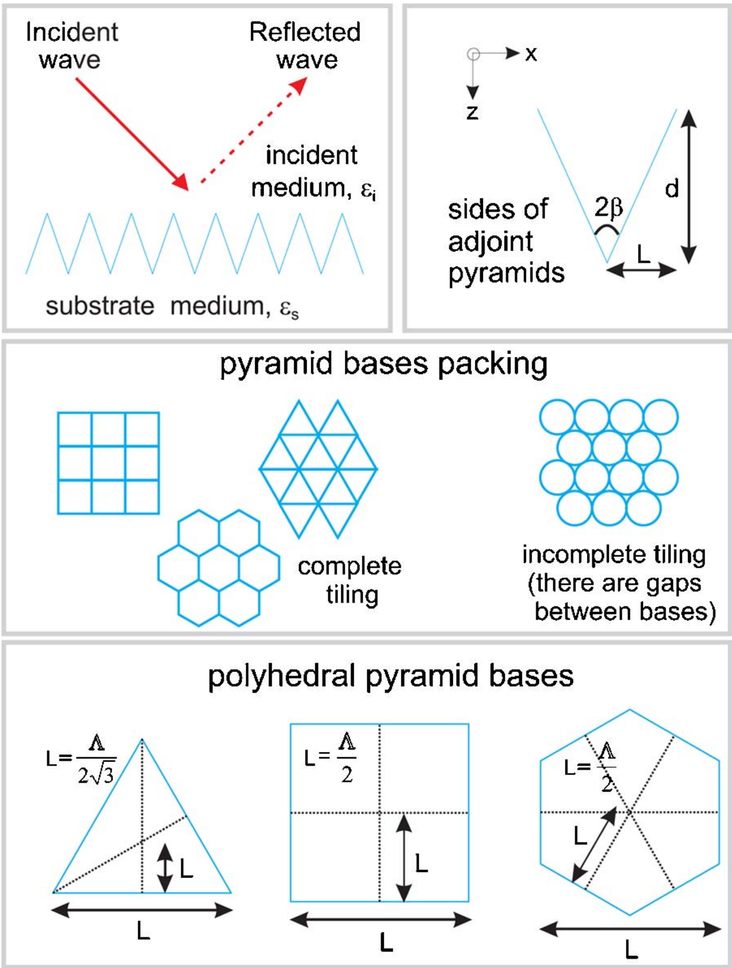
- Effective gradient-index material
- Reflectivity is complicated:

$$\rho = -\int_0^{g(d)} h e^{-ig/\lambda} \mathrm{d}g = \sum_{k=1} (-i)^k \lambda^k h^{(k-1)} e^{-ig/\lambda} \Big|_0^{g(d)}$$

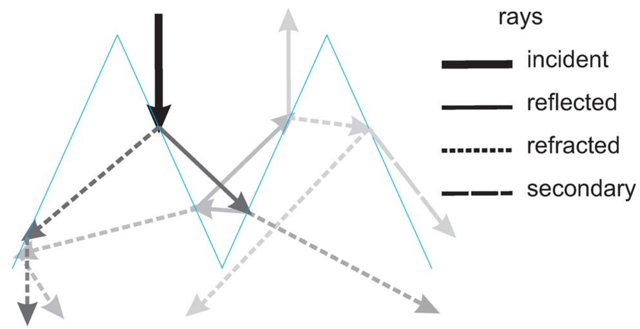
- Linear profile: R ∝ $(d/\lambda)^{-2}$
- Breaks down when d ~ λ

Theory *(cont.)*

(from Deinega *et al.*, *JOSA A* **28**(5), 2011)



- Short λ limit (λ≪L):



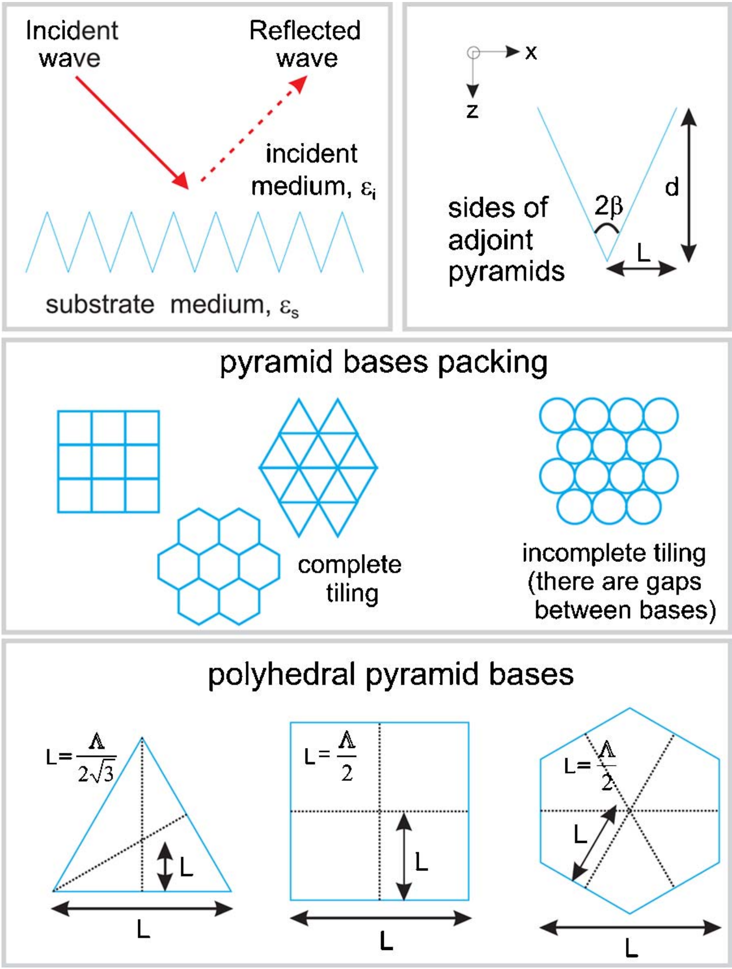
- Geometric optics (forest traps light)
- Reflectivity:

$$R_{\mathrm{refl}} \approx \exp\left(-C\frac{d}{L}\right)$$

- Doesn't necessarily break down, since n→1 as λ→0

Theory *(cont.)*

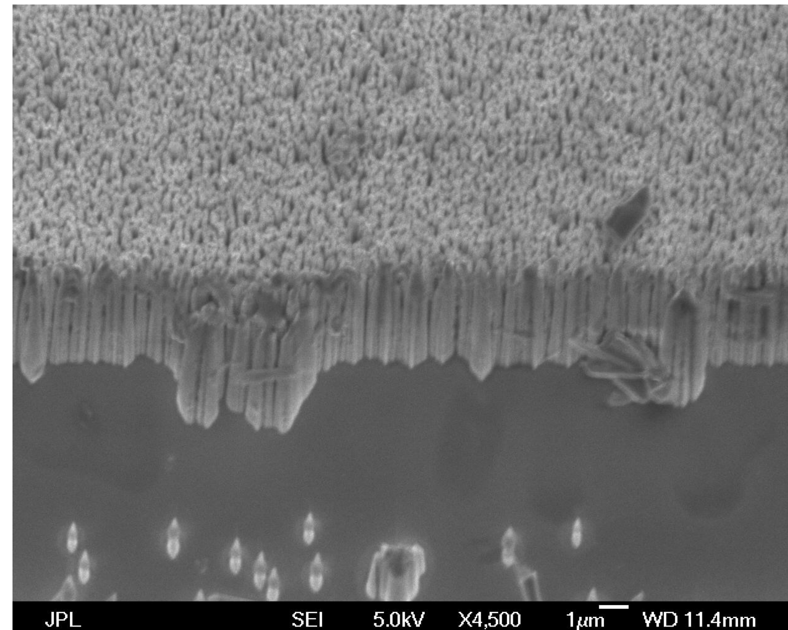
(from Deinega *et al.*, *JOSA A* **28**(5), 2011)

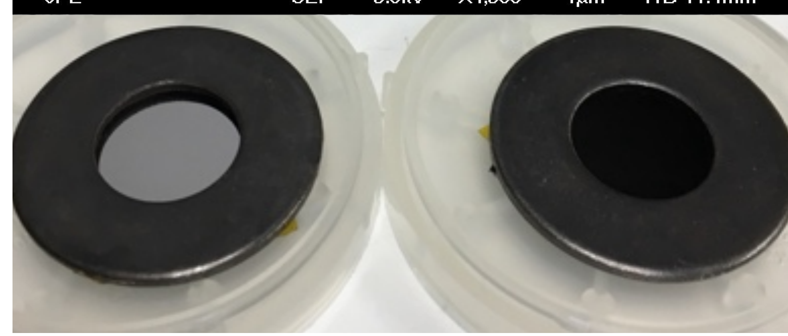


- Intermediate λ limit (λ ~ L): Neither picture is quite true
- Full FDTD Maxwell simulations necessary
- But in general, reflectivity still suppressed

Optimized Micromasked Etch

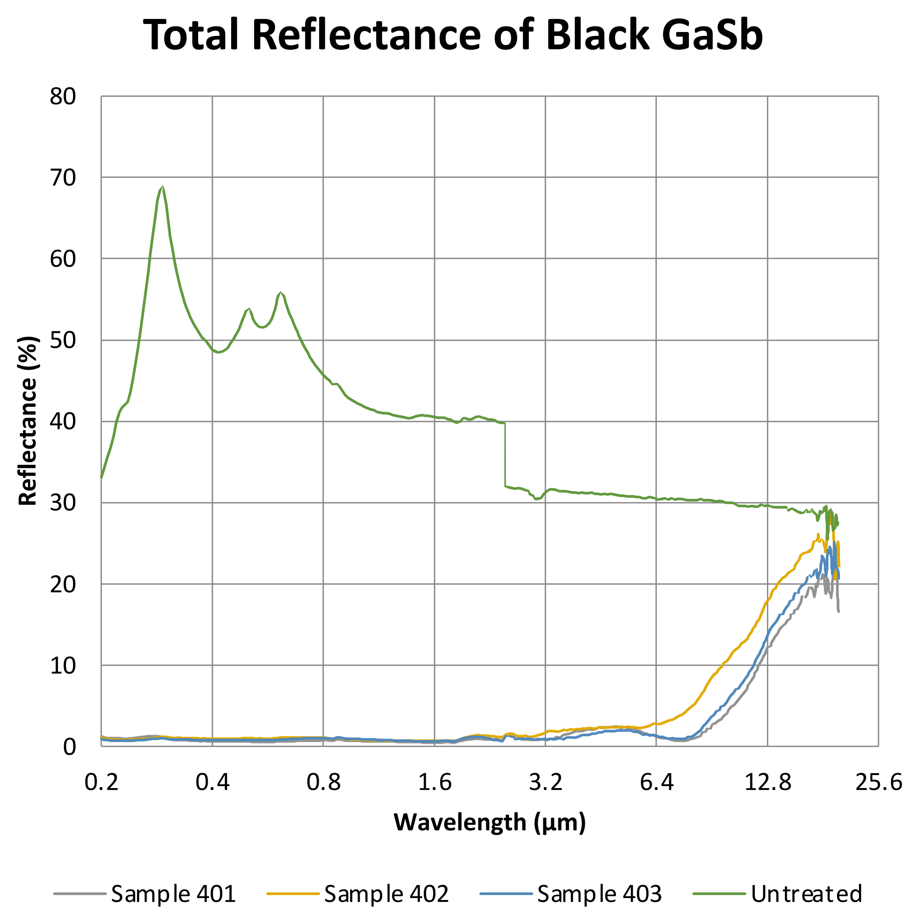
- Adapted Cl_2/O_2 micromasked ICP etch process of Lin *et al.*, *Nano Lett.* **15**(8), 2015
  - Tuning of etch parameters for our chamber and optimization of height, width, density
- Performed etch on highly-doped GaSb to avoid back side reflection (highly absorbing substrate)
- Examined specular and diffuse reflection





Total Reflectance

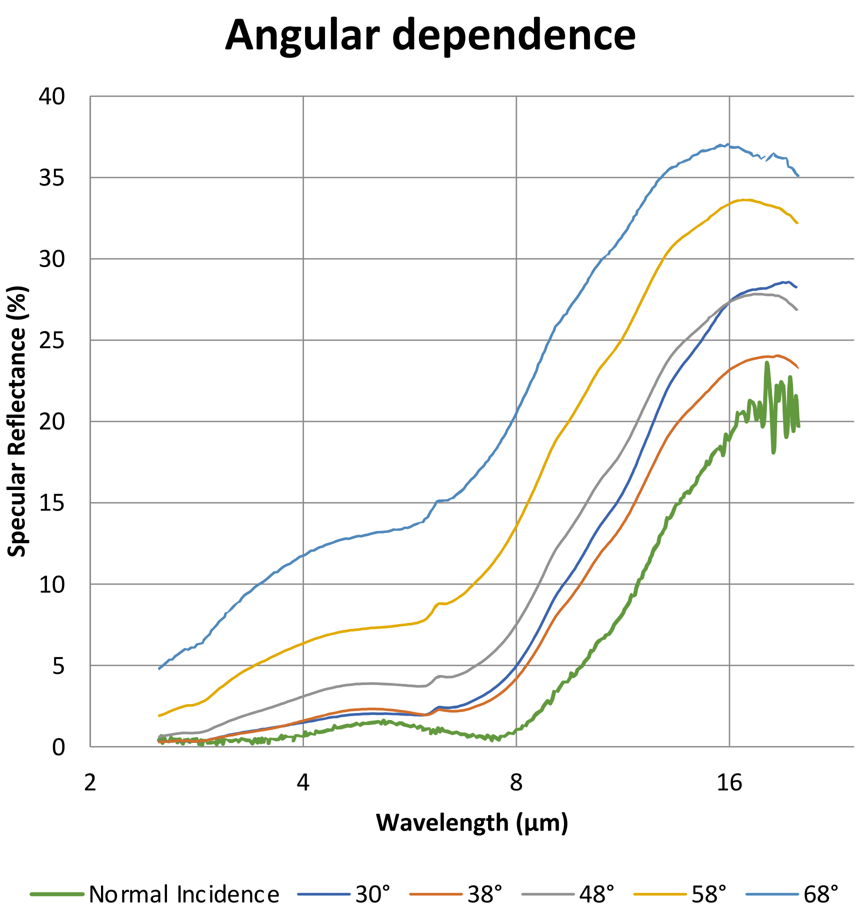
- Sub-10% total reflectance from 200 nm to 12.2 µm
- Nearly 6 octaves*!
- Reflectance primarily specular; diffuse reflectance under 1%
- Not very optimized; black silicon routinely achieves antireflection out to 25 µm



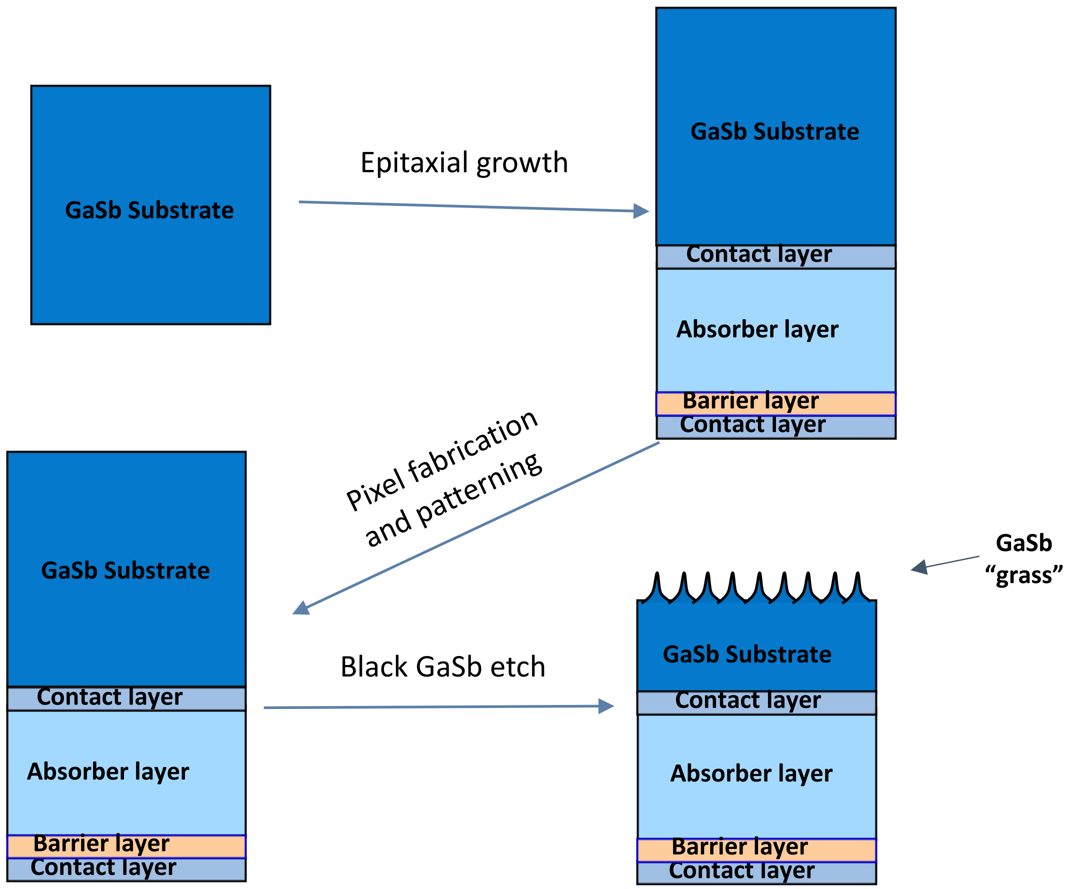
* Of course, GaSb is absorbing below bandgap

Specular Reflectance vs. Angle of Incidence

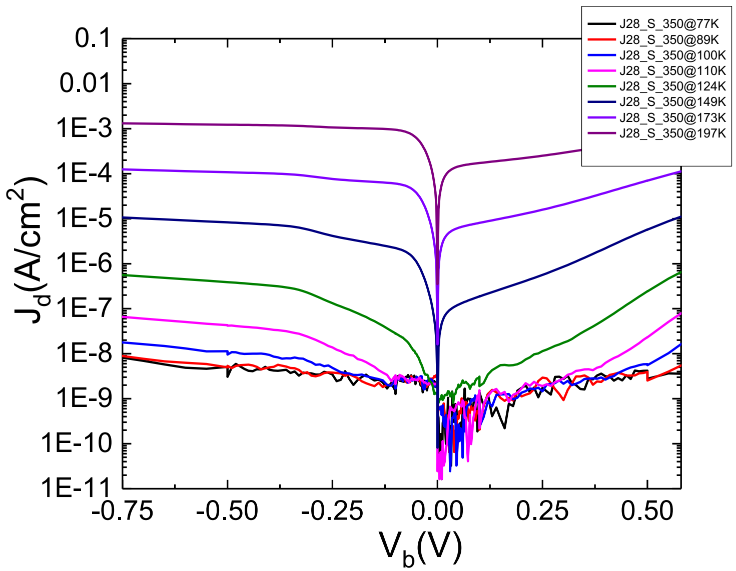
- Specular reflectance vs. angle of incidence for sample 403
- Demonstrate antireflectivity for angles of incidence from normal to 58°
- Not very optimized; black silicon has achieved 70°

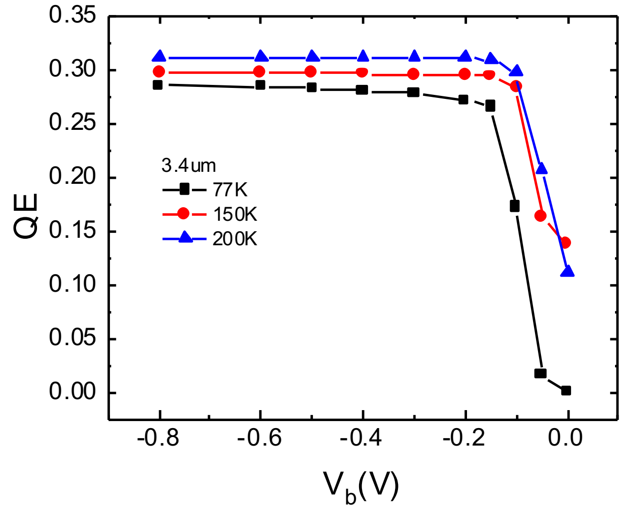


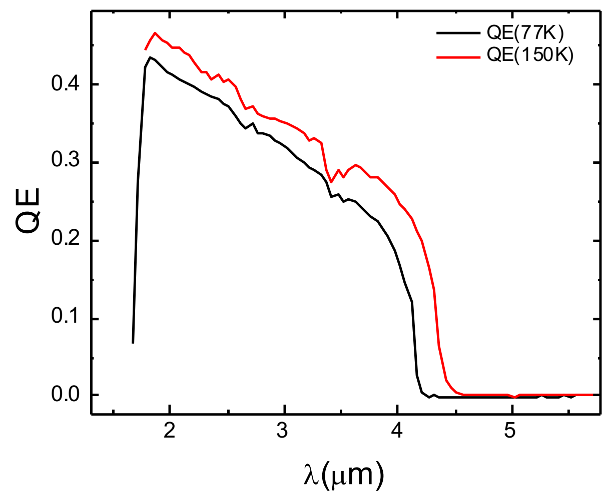
Integration of Black GaSb w/ Infrared Detector
(patent pending)



Bulk InAsSb nBn Before Etch
(patent pending)







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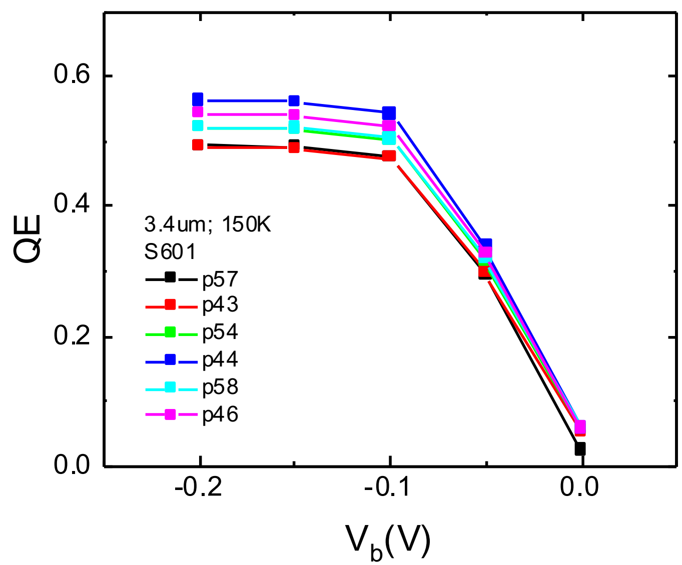

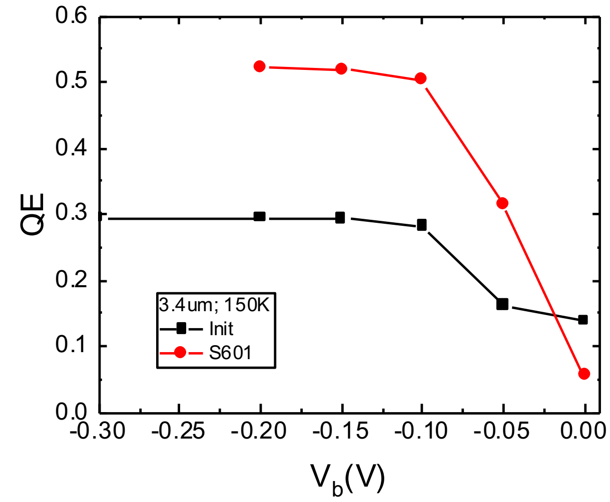

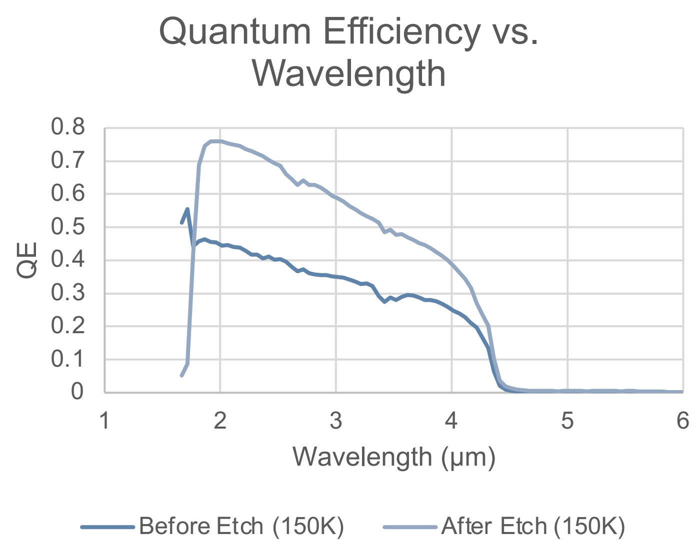

Conclusion

- Improvement of micromasked Cl_2/O_2 ICP etch technique originally from Lin *et al.*, *Nano Lett.* **15**(8), 2015
- Demonstration of antireflective “black” GaSb at wavelengths from 200 nm to 12.2 μm (nearly 6 octaves!) and at angles of incidence from normal to 58°
- Integration of black GaSb with infrared detectors **(patent pending)**
  - Demonstration on bulk InAsSb nBn
  - Demonstrated QE improvement from ~30% to ~50%
  - Advantages over dielectric coatings (bandwidth, angle of inc., delamination, simplicity)

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