All-Epitaxial Mid-Wavelength Infrared Resonant Cavity-Enhanced Photodiodes

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III-V semiconductor-based mid-wavelength infrared (MWIR) detectors have reached a point of diminishing returns in the drive towards reduced dark current. To realize a significant improvement in dark current magnitude, new concepts and approaches must be explored. One approach is to reduce the thickness of the optical absorber of the detector. Typical MWIR detectors require several micron thick absorbers in order to absorb most of the light and obtain high quantum efficiency. This results in elevated dark current as dark current is directly proportional to optical absorber thickness [1]. One approach to reducing optical absorber thickness is to place a thin optical absorber within a resonant cavity between high reflectivity mirrors, similar to vertical-cavity surface emitting laser (VCSEL) structures. This resonant cavity-enhanced photodiode (RCE-PD) architecture creates many optical passes through the absorber, allowing an absorber which is 50-100x thinner than conventional MWIR detectors while offering other unique features including: narrow spectral linewidth, reduced dark and background current, and enhanced detection at cavity resonance.

We report on all-epitaxial MWIR RCE-PDs via MBE. Distributed Bragg reflector upper and lower mirrors are deposited on either side of an optical cavity containing a thin MWIR optical absorber via a single growth. Results show dark current magnitudes near or below Rule07 [2] at the cut-off wavelength of the absorber, spectral linewidths <40 nm, and a 300K D* > $1x10^{10}$ cm $Hz^{1/2}$ W^{-1}. Creating an all-epitaxial RCE-PD requires careful epitaxial design and exact control of MBE growth parameters which will be discussed.

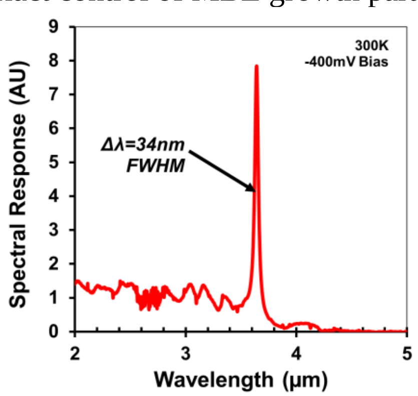

Figure 1. RCE-PD with a 34nm FWHM spectral linewidth at 3.6μm resonance.

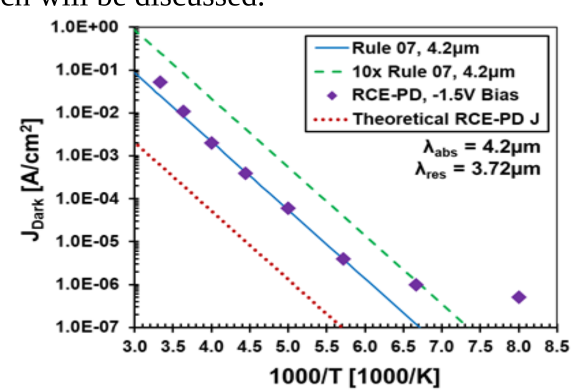

Figure 2. Dark current of a 3.72μm RCE-PD matches Rule07 at absorber resonance.

[1] G. R. Savich, *et al*, Applied Physics Letters 106(17), 173505 (2015).
[2] W. E. Tennant, Journal of Electronic Materials 39(7), 1030-1035 (2010).

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Supplementary Information:

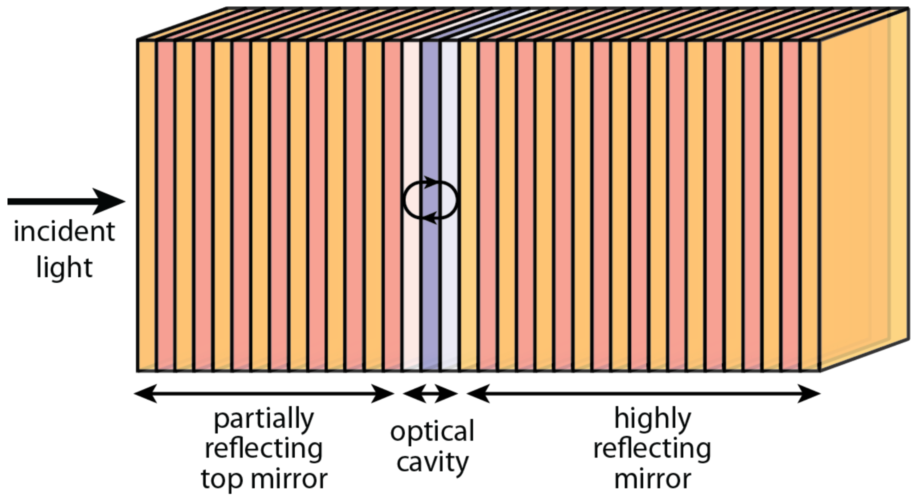

Figure 3. Schematic of an all-epitaxial RCE-PD. The highly reflecting back mirror and the partially reflecting top mirror are deposited via MBE as a distributed Bragg reflector consisting of λ/4 layers of two differing, large bandgap III-V materials lattice-matched to the substrate (GaSb in this case). Between the reflectors, an optical cavity is deposited consisting of two large bandgap spacer layers (also lattice matched) and a thin MWIR optical absorber.

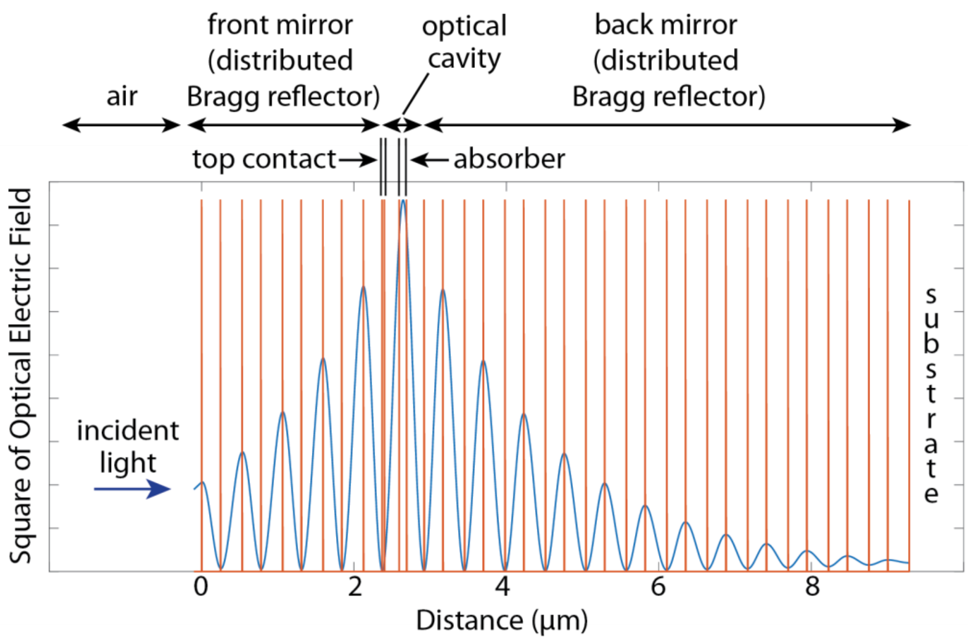

Figure 4. Epitaxial Design of the all-epitaxial RCE-PD is non-trivial. The optical absorber must be placed on an anti-node of the optical electric field within the resonant cavity to ensure the highest level of MWIR detection. Furthermore, the narrow-bandgap top contact layer must be placed on a node of the optical electric field to ensure minimal photon absorption within the top contact.

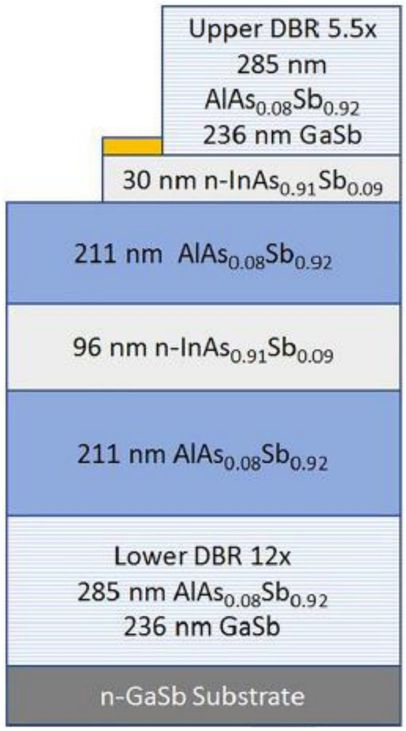

Figure 5. An all-epitaxial, MBE grown RCE-PD detector structure designed for resonance near 3.7µm. The optical absorber is InAsSb lattice matched to GaSb (4.2 µm cut-off wavelength at 200K) to ensure the lowest possible defect density within the optical absorber despite the resonant wavelength of the cavity, 3.7µm. All materials in the structure are lattice-matched to the GaSb substrate. Control of the thickness of all cavity layers is critical to maintaining a consistent cavity resonance. This is a significant challenge to the MBE grower.

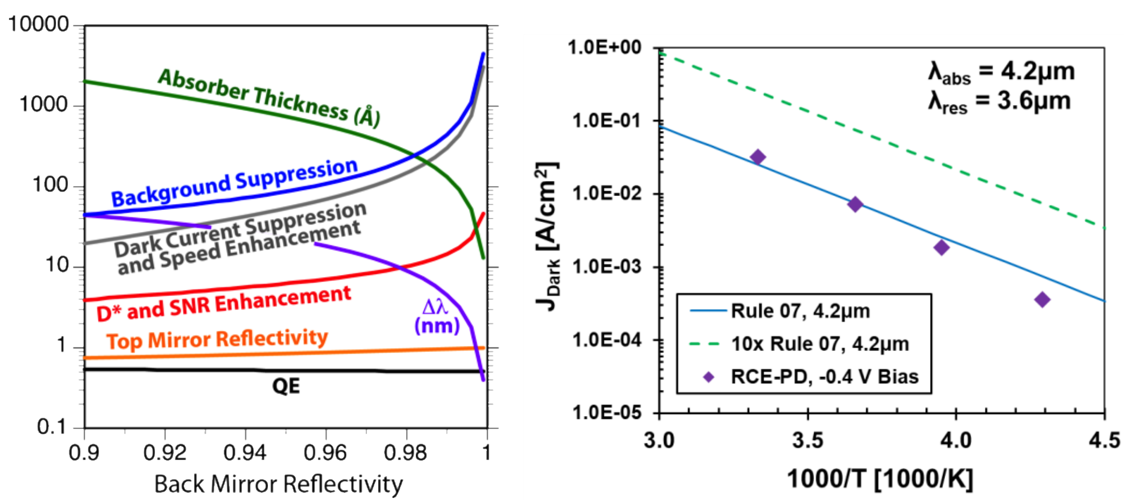

Figure 6. *Left*- The RCE-PD architecture offers a unique performance trade-off space which is largely dependent upon the reflectivity of the back mirror. As the back mirror reflectivity increases, the required absorber thickness and the spectral linewidth, *Δλ*, decrease. These two effects result in enhanced background photocurrent suppression, dark current suppression, detector speed, D*, and SNR. *Right*- A 3.6µm RCE-PD with an optical absorber cut-off wavelength of 4.2µm exhibits dark current densities equal to or less than Rule07 at the absorber cut-off wavelength. Further reduction in dark current is possible via refinement of the epitaxial design and MBE growth of the RCE-PD cavity region which completely controls the magnitude of the dark current of the device.