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Long-wavelength Infrared Detection Using Self-Assembled Quantum Dots

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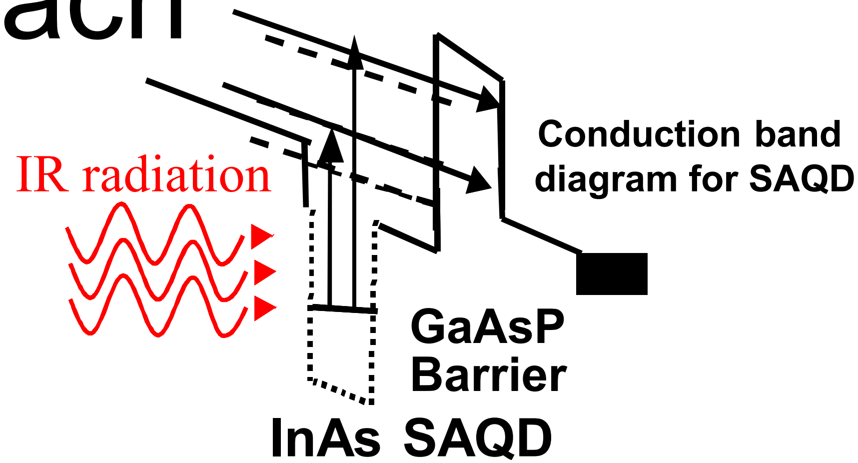
Problem

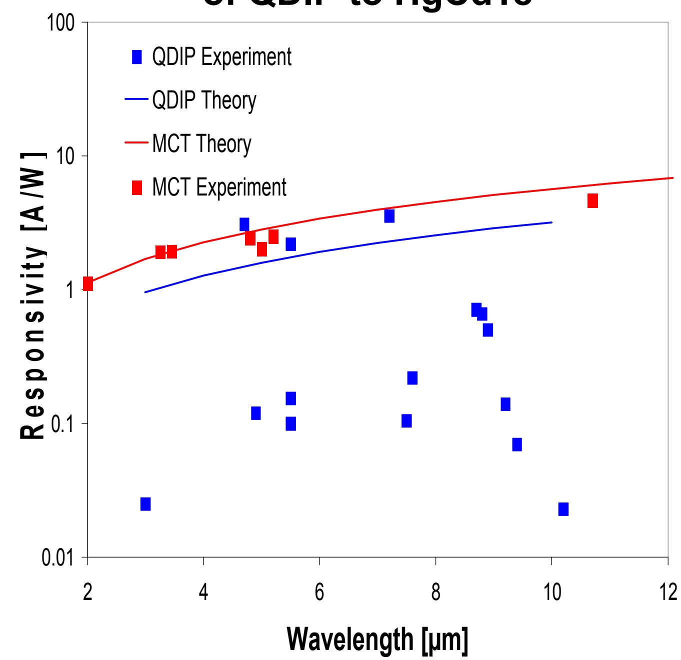
- Current long-wavelength infrared (LWIR, 10 to 12 µm) detectors and focal plane arrays (FPAs) use HgCdTe and operate at cryogenic temperatures (77 K)
  - HgCdTe detectors are very good D^* > 3E11 cm $Hz^{1/2}/W$ at 10 µm at 77 K.
- Desire an alternative detector that could:
  - Operate at higher temperatures
  - Potentially have higher performance
  - Utilize a more flexible materials technology that could be integrated with electronic device structures

Approach

- InAs self-assembled quantum dots (SAQD) embedded in GaAs have intrasubband (electrons only) transitions between 100 and 150 meV.
  - Use InAs SAQD has a active medium for LWIR detection
- Model calculations suggest that quantum dot infrared photodetectors (QDIP) will have responsivities close to the performance of HgCdTe photodetectors.
  - Limited experimental results suggest that QDIP performance can exceed model predictions at lower wavelengths.



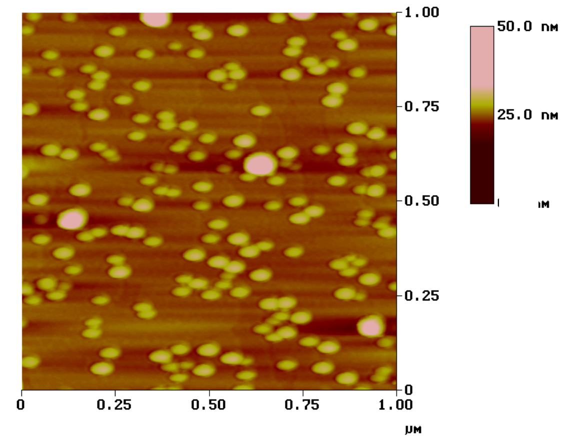
Performance comparison of QDIP to HgCdTe



Challenges

- Sandia has necessary experience and infrastructure to evaluate QDIP devices.
- SAQD have a low surface density (5E10 to 1E11 cm^{-2}). Need a large thickness of SAQD to provide sufficient quantum efficiency.
  - Generate multiple layers of SAQD to increase active volume.
- Strain in SAQD multilayer may produce performance degrading defects making.
  - Use strain-balanced multilayer to limit driving force for defect formation.
- Identified lower limited on detectivity for advancing single pixel detectors toward integrated FPA.
  - Single-pixels need to have detectivity of 5E10 cm $Hz^{1/2}$/W or greater

Atomic Force Micrograph of SAQD



Strain-balanced SAQD multilayer structure

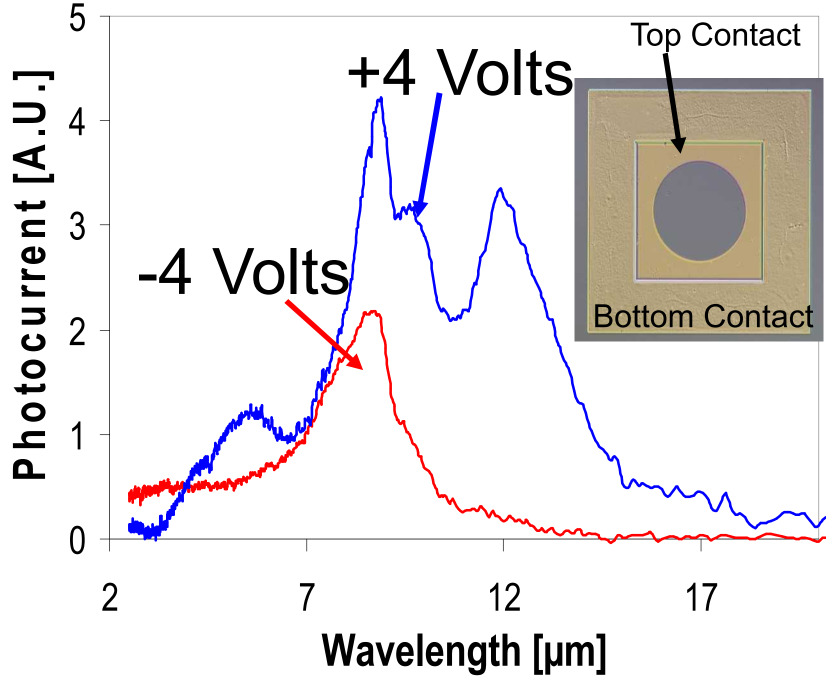
0.2 μm GaAs contact (n ~ 2E18 cm^{-3})
0.05 μm GaAs undoped
250 Å GaAs undoped
250 Å $GaAs_{0.9}P_{0.1}$ undoped
50 Å $In_{0.15}Ga_{0.85}As$ undoped
6.1 Å InAs (n ~ 2E18 cm^{-3})
0.05 μm GaAs undoped
0.5 μm GaAs contact (n ~ 2E18 cm^{-3})
Semi-insulating GaAs substrate

Repeat period

QDIP spectral response

- Initial results showed optical response of SAQD around 9 μm (138 meV) with voltage tunable response at 12 μm (100 meV)
  - Response tunable by varying thickness of InGaAs capping layer and GaAsP strain-balancing layer.
- Detector operates at 80 K.
  - Missed target of 100 K.

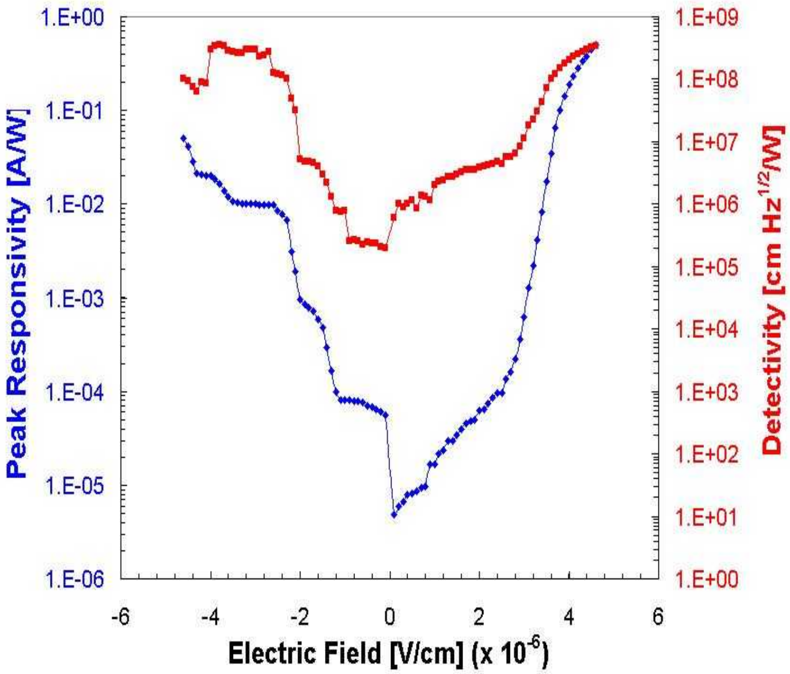
IR response spectrum of QDIP



Calibrated response of QDIP

- Calibrated responsivity of detector is state-of-the-art
  - 0.5 A/W at 80 K
  - Lower than modeled responsivity
- Detector detectivity is very low
  - 3.4E8 cm $Hz^{1/2}$/W at 80 K
- Low detectivity due to high dark current of device.
  - Need to lower dark current
    - Improve uniformity of SAQD
    - Calibrate density of electrons needed for QDIP operation
    - Improve QDIP pixel design

Calibrated response of QDIP at 9 µm



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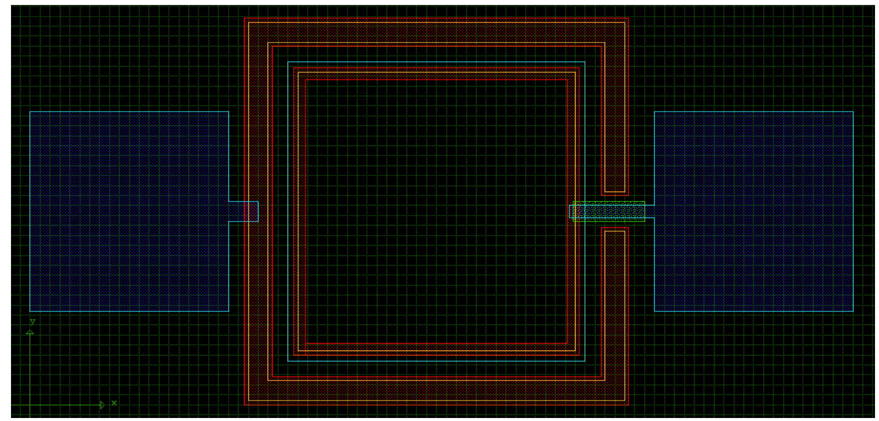
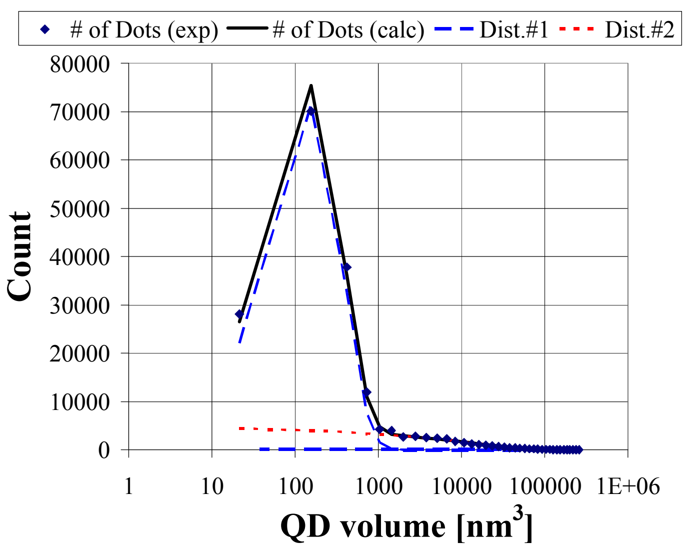
Improvements of QDIP design

- Developed scalable pixel that limits lower perimeter/area of detector
  - Dark current scales with perimeter/area ratio
- Improved uniformity of SAQD
  - Through collaboration with NIST-Boulder investigated conditions to give uniform SAQD

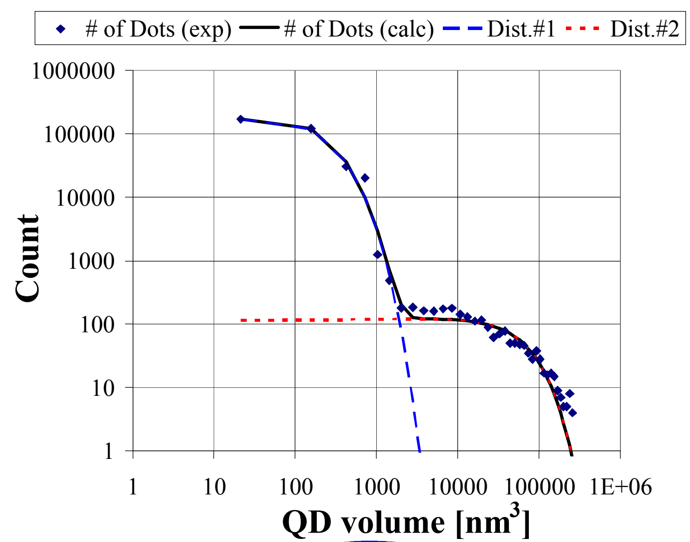
Scalable pixel for reduced perimeter/area



Standard conditions of SAQD growth



Improved conditions of SAQD growth



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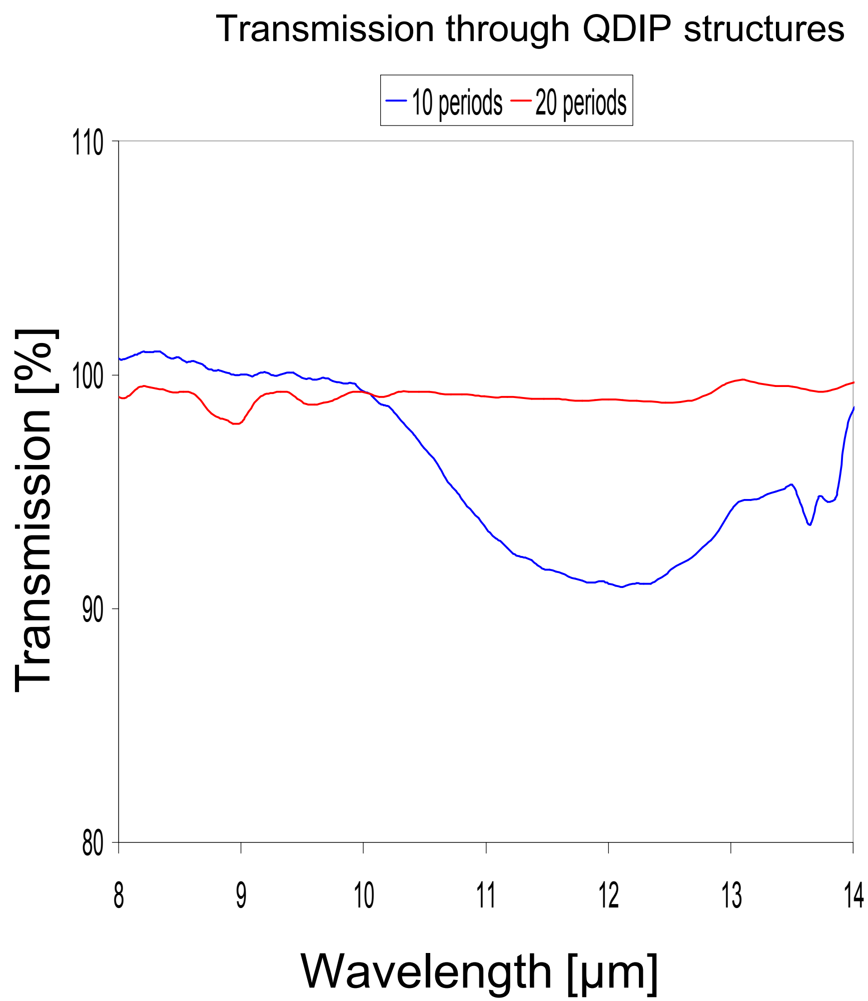
Strain-balanced QDIP

- Investigate impact larger active volume has on amount of absorbance
  - Thicker QDIP has degraded response
- Defects possibly formed during epitaxy
  - Strain-balancing cannot produce the higher active volumes needed
  - Cannot trade larger responsivity of thicker QDIP to offset large dark current to get improved detectivity



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Significance

- Direct replacement HgCdTe detector technology by QDIP seems unlikely.
  - QDIP may have niche applications for LWIR and VLWIR (greater than 15 μm) detection if dark current can be reduced further.
  - QDIP may be able to have response times not possible with HgCdTe.
  - Desire to have a viable replacement for HgCdTe still strong.
- Demonstrated QDIP platform for future scientific investigations and engineering development.
  - Investigating use of surface plasmons to enhance responsivity and control polarization of detected radiation.
- Interest in intrasubband transition in SAQD led to investigation of using them as LWIR emitters in cascaded structure.
  - Separate LDRD continuing to advance this investigation.