SAND2018-3683C

Resonant Ultrathin Infrared Detectors Enabling High Quantum Efficiency

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Abstract: We demonstrate thinned resonant longwave infrared detectors with quantum efficiencies of over 60% in the longwave infrared. This improvement over unthinned detectors is made possible by a nanoantenna that confines the incident optical energy in a reduced volume compared to traditional detector architectures.

Index Terms: Detector, focal plane array, infrared, nanoantenna, metamaterial.

1. Introduction

Longwave infrared detectors tend to have a lower external quantum efficiency than their midwave and shortwave infrared counterparts. This hinders applications that have low flux levels. For the case of type-II superlattice detectors (T2SL) in particular, the majority in the long-wavelength infrared band have suffered from a fairly low absorption coefficient and shorter diffusion length than mercury cadmium telluride (MCT) detectors. While thickening of the absorber material can improve EQE, it has the undesirable consequence of increasing dark current, potentially reducing the signal-to-noise ratio. Moreover, the thickness is limited by the diffusion length of the carriers. Thus, alternative methods that investigate changing the detector architecture rather than the detector material are required.

A resonant detector structure, presents a path towards substantial gains in detector response without the need for increased detector thickness or absorption coefficient. This is the result of the increased field strength in the detector layer that can be obtained through a resonant cavity. While this architecture is not necessarily limited to superlattice detectors and could be employed in MCT detectors, the advantages of a thinner layer are particularly advantageous for our T2SL detectors. [1]

We incorporate a nanoantenna, a subwavelength metal patterning, on the top surface of the detector, as shown in Figure 1. This patterning may be alternatively referred to as a metasurface or a frequency selective surface. The nanoantenna matches the detector stack and bottom ground plane to freespace. This allows a reflection-free surface without the need for an antireflection coating. It is also angularly insensitive for tens of degrees: enough for any practical system. The nanoantenna can be designed to accommodate a very thin active layer. The significant reduction (roughly an order of magnitude) in overall volume of the active layer leads to a reduction in the dark current produced in the bulk of the detector material.

This nanoantenna-based architecture has been simulated, fabricated, and characterized using T2SL detectors. The resulting external quantum efficiency at the resonant wavelength is up to 3X higher than what is measured for an equivalent thick detector with a traditional architecture using the same detector material. The thin detector architecture should also reduce dark current

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due to the much-reduced volume of active material and reduce crosstalk between pixels as the aspect ratio will lead to a significant decrease in excited carriers collected in adjacent pixels as compared to traditional detector pixels.

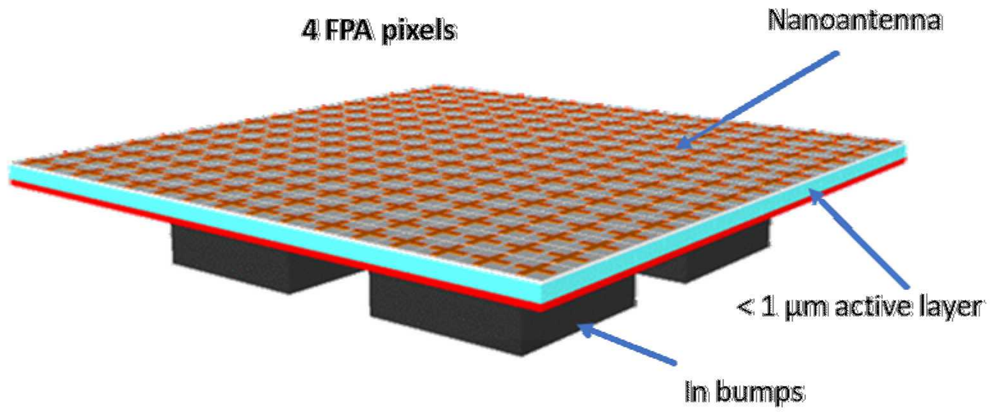

Fig. 1. Visualization of four pixels of a focal plane array using a top patterned layer to create an efficient resonant cavity with near zero reflection. The majority of light is then absorbed in the thin active layer. Indium bumps connect to a standard ROIC.

2. Design and Simulation

A variety of modeling methods are employed to simulate the optical response and design nanoantennas for specific wavelengths and. Rigorous coupled wave analysis (RCWA) is used to model the infinitely periodic case. For specific nanoantenna designs we have developed a circuit model that allows rapid optimization of nanoantenna patterns for various detector stacks [2].

Periodic boundary conditions of a nanoantenna unit cell does not include effects at the boundary of a focal plane array pixel. Here the nanoantenna periodicity is interrupted. The boundary between pixels affects the overall quantum efficiency of the device, and thus it is important to model the boundary and design the nanoantenna to mitigate any losses. For this a full electromagnetic modeling code is required. The large structure size requires large computational resources. We will show results run on our high-performance computing resources.

To ensure modeling results that have high fidelity, we measure the optical constants of the active layer and the metal used for the nanoantenna. These values for thin metal layers may differ considerably from bulk values and Drude approximations. Superlattice optical constants are considerably more complex as the layered structure leads to an anisotropic refractive index. Incorporation of these measured values into the electromagnetic models and the circuit model have led to good agreement with experimental results.

3. Fabrication and Integration

The designed structures were fabricated. Superlattice layers are grown on a GaSb wafer. Passivation of sidewalls after mesa etching is performed using silicon nitride. The wafer is flipped onto indium bump bonds and underfilled with epoxy. The original GaSb wafer may now be removed through mechanical and etch processes, leaving the thin epitaxial layers (under 1 µm active layer) attached to the new electrical read-out substrate. The nanoantenna is then patterned on what is now the top surface of the detector.

4. Characterization

Fabricated devices were characterized at a temperature of 60 K for external quantum efficiency. The external quantum efficiency (EQE) was measured to be nearly 60% at a temperature of 60K (as shown in Figure 2). It is almost 3X higher than the quantum efficiency of the same detector layer without a nanoantenna structure.

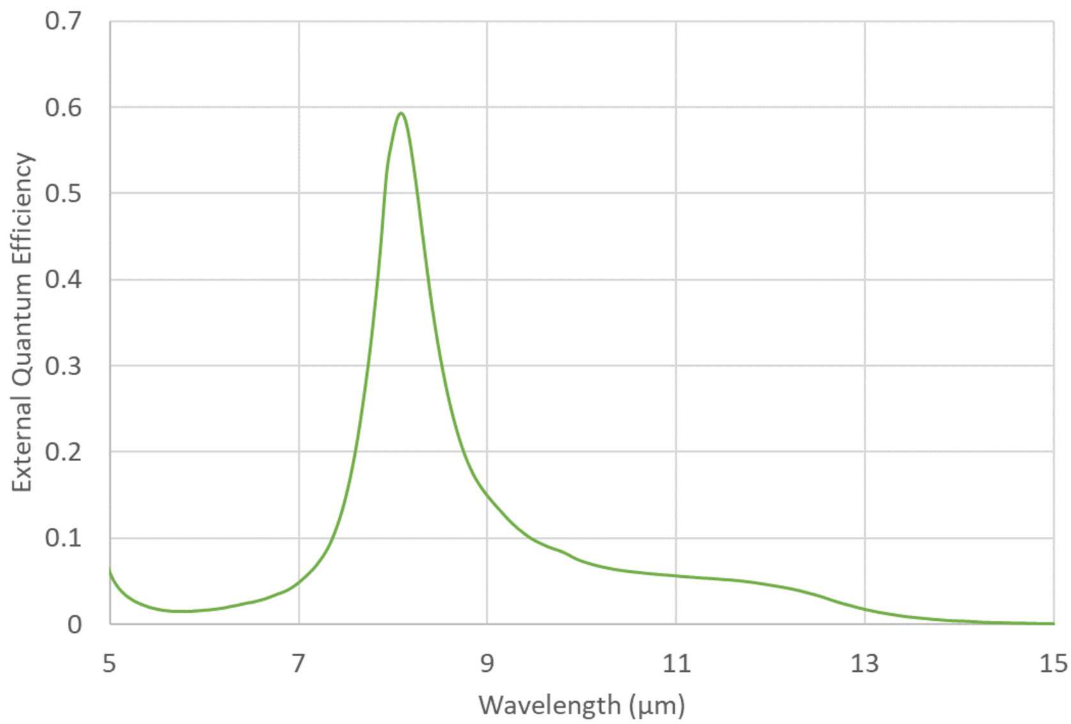

Fig. 2. Measured external quantum efficiency of a nanoantenna-enabled thin detector. Total active layer thickness is approximately one freespace wavelength at the resonant wavelength. Measurement taken at 60K.

Tailoring of the nanoantenna design allows us to move this resonant peak across the thermal infrared band, allowing enhancement out to the material cutoff. The nanoantenna pattern can be changed from pixel to pixel, allowing multispectral options. The 1µm bandwidth of this resonant cavity is typical, but may be widened significantly through nanoantenna design, either through different unit cell patterns or use of a supercell design. [3]

5. Conclusions

These early results prove the validity of our device concept as well as our ability to fabricate and characterize these revolutionary photodetectors. We have also demonstrated that we can tailor the resonance wavelength within the 8-12 µm band, and the resonant bandwidth between 1-2 µm widths.

Resonant T2SL architectures offer significant advantages over a traditional detector architecture, though with somewhat added complexity in manufacturing. These advantages are compelling however, as high external quantum efficiency and low dark current are possible and have been demonstrated. External quantum efficiencies of ~60% have been demonstrated at wavelengths near the cutoff wavelength of the detector: values that are much higher than the same material without the nanoantenna-enhanced resonant structure. Our models show that this is not a fundamental limitation, and that external quantum efficiencies around 70% are realistic to expect. These results illustrate the utility of this architecture with detector materials with relatively low absorption coefficients.

Acknowledgements

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