Australian Government
Department of Defence
Science and Technology

EDTAS
EMERGING DISRUPTIVE TECHNOLOGY
ASSESSMENT SYMPOSIUM

Recent progress in semiconductor nanowire photodetectors for multispectral imaging

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POSTERA CRESCAM LAUDE

Longer term broad strategic aspects & perspective

Symposium questions (*SQs*) that were requested by organisers:

SQ1. Their perspective of the technical and societal trends, barriers and drivers (relevant to AMM) for their presented topic.

SQ2. Current gaps in knowledge (or science base) that are essential bridge in order for the presented topic to have broad impact.

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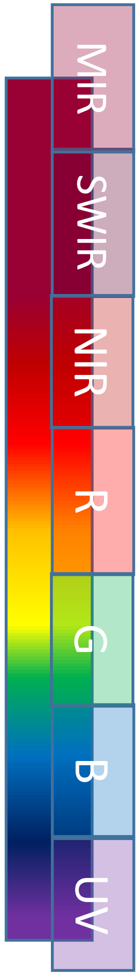
What is Multispectral Imaging?

A multispectral image is one that captures image data at specific frequencies across the electromagnetic spectrum. The wavelengths may be separated by filters or by the use of instruments that are sensitive to particular wavelengths, including light from frequencies beyond the visible light range, such as **infrared**.
-Wikipedia



Multispectral Imaging System

Filter wheel

http://www.pixelteq.com

Sensor box with 12 multi-spectral sensors (two upper rows) and 6 thermal infrared sensors (bottom row)
Australian **A**irborne **C**al/val **E**xperiment for **S**MOS

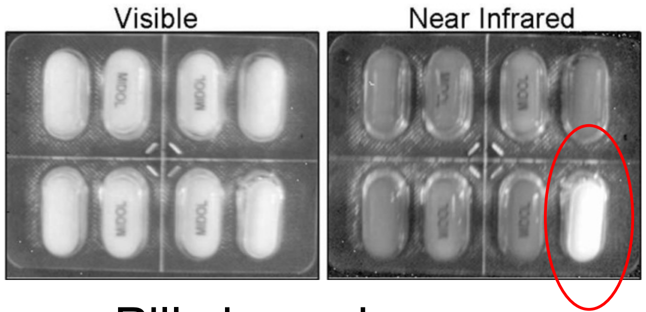
Applications of Multispectral Imaging - From Visible to Infrared

THE UNIVERSITY OF MELBOURNE

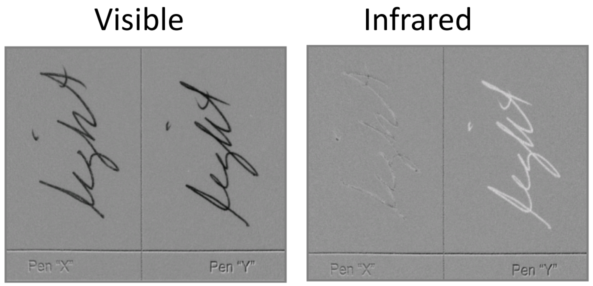
Remote sensing: vegetation monitoring

Enhanced imaging (low light, fog)

Anti - Counterfeit



Pills in package



Signatures from different ink

The potential of nanowire multispectral imaging

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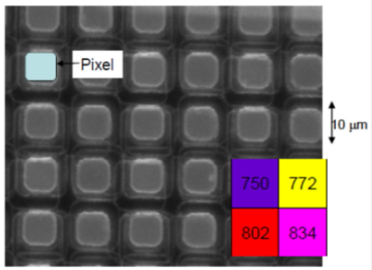
Conventional Multispectral Imaging

- Bulky Filter wheels
- Multiple sensors or focal plane filter arrays
  - Expensive
  - Fabrication complexity

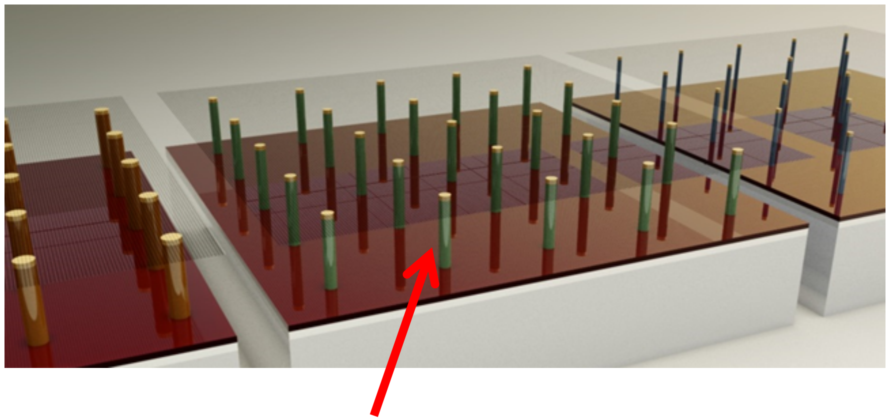
http://www.pixelteq.com



Eichenholz et al,
Proc. SPIE 7568 (2010)

Nanowire Multispectral Imaging

- Nanowires as light sensors ("photodetectors")
- Spectrally selective nanowires - no filters are needed!



Nanowire (NW), e.g. silicon or germanium

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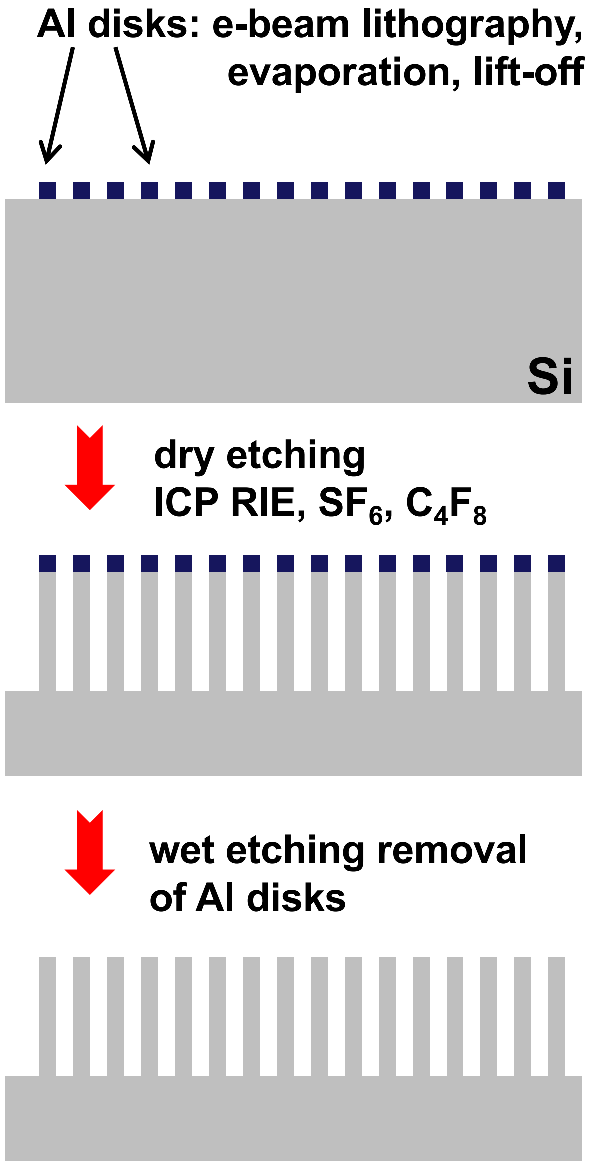
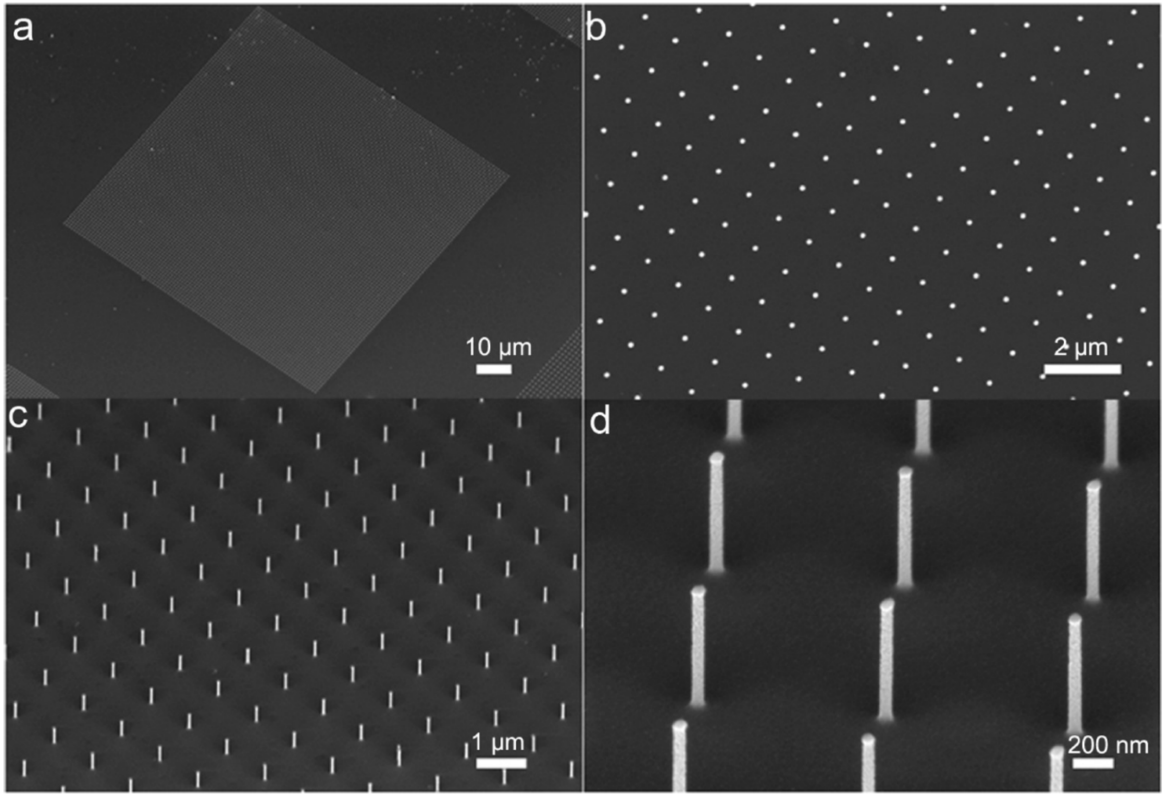
Silicon nanowires – via etching



SEM images of vertical silicon nanowire array



- Overall extent of nanowire array is 100 µm by 100 µm
- Nanowire pitch a = 1 µm, radius = 45 nm, length = 1 µm

- Dry etching enables formation of well-ordered arrays of Si nanowires with excellent control of size & shape

Multicolored vertical Si nanowires

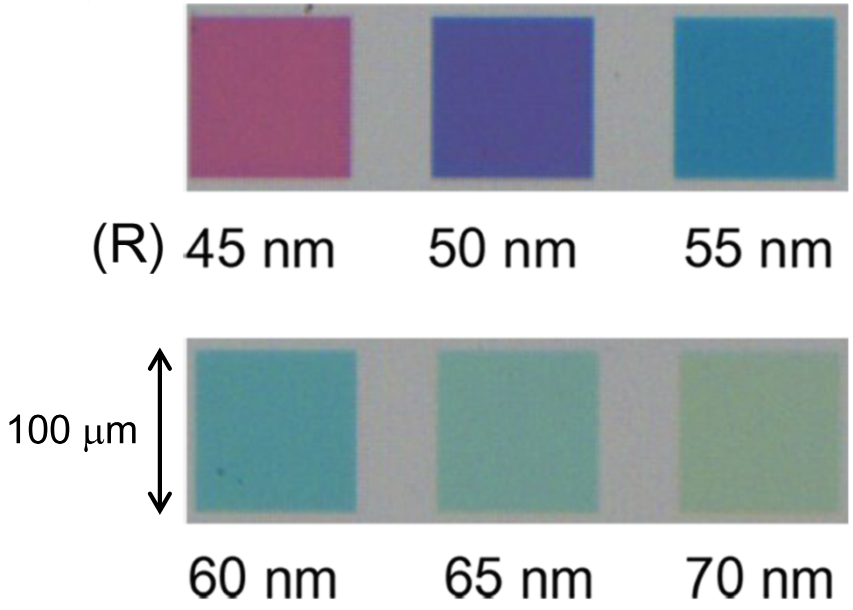
Scanning electron micrograph

Optical microscope image

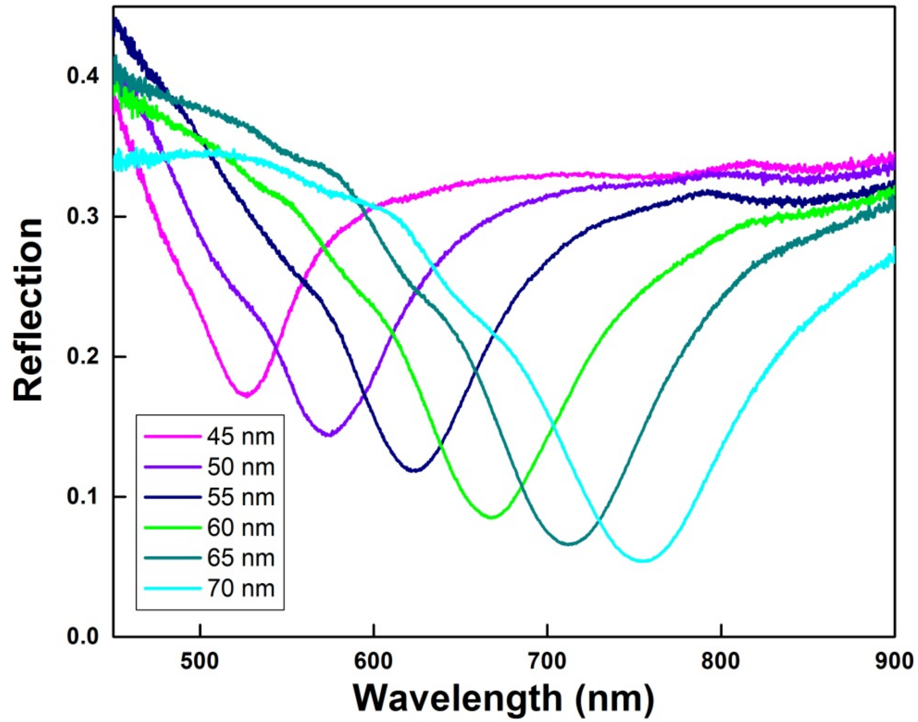
- We fabricated an "arbitrary" pattern of Si nanowires
- Radii of nanowires in "S", "E", "A", "S" are 70, 60, 50 & 40 nm
- Nanowire params: length, pitch = 1μm
- Nanowire colors cover the visible spectrum, when viewed in a regular optical microscope

Multicolored vertical Si nanowires

Optical microscope images of nanowire arrays

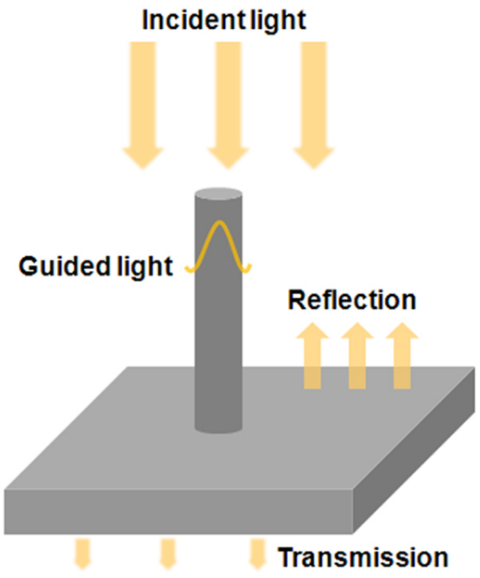


Measured reflection spectra of nanowire arrays



- We fabricated square arrays of nanowires with radii (R) from 45 to 70 nm
- Nanowires are 1 μm long, on a 1 μm pitch. Overall array extent: 100 × 100 μm
- Measured reflection spectra show a “dip” whose positions depends on radius

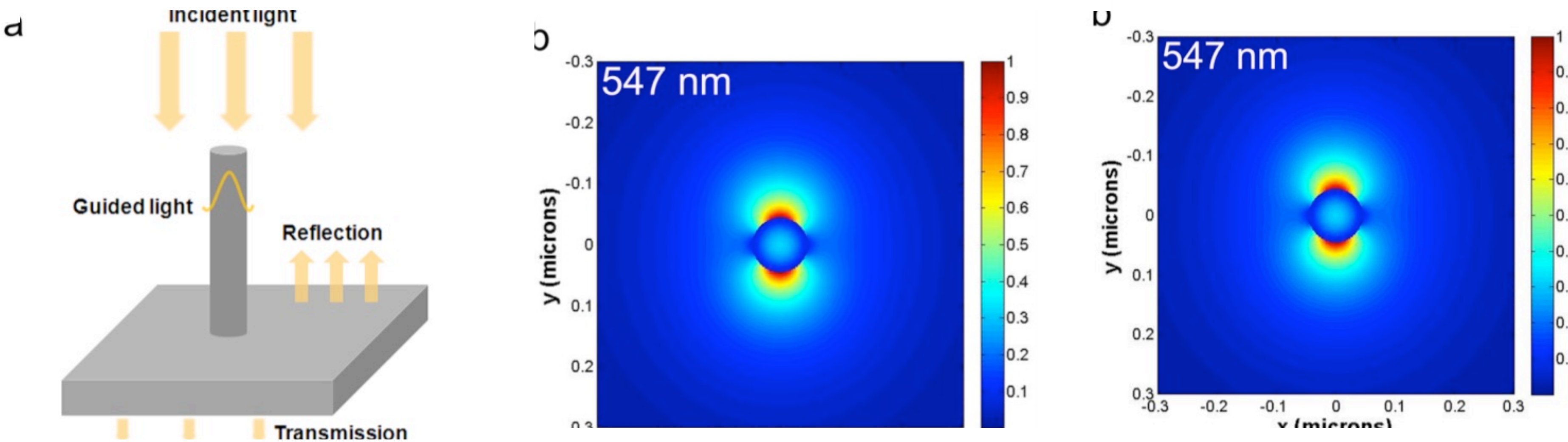
Physical interpretation



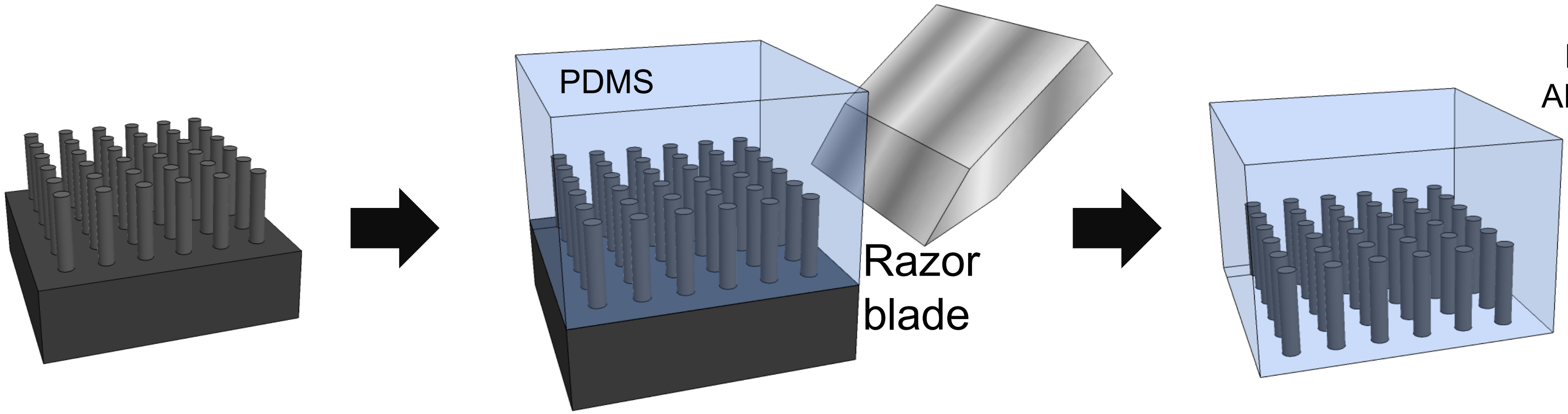
- "Multicolored" nature originates from λ-dependence of field distribution of fundamental guided mode
- Short λ (= 400 nm): mode tightly confined to nanowire. Incident light does not efficiently excite mode as spatial overlap very poor
- Long λ (= 650 nm): modal field mostly expelled from nanowire. Mode can be efficiently excited, but absorption is very low.
- Intermediate λ (= 547 nm): efficient excitation AND absorption

Fundamental mode ($HE_{1,1}$) of Si nanowire at three representative wavelengths

Major transverse component (E_y) plotted



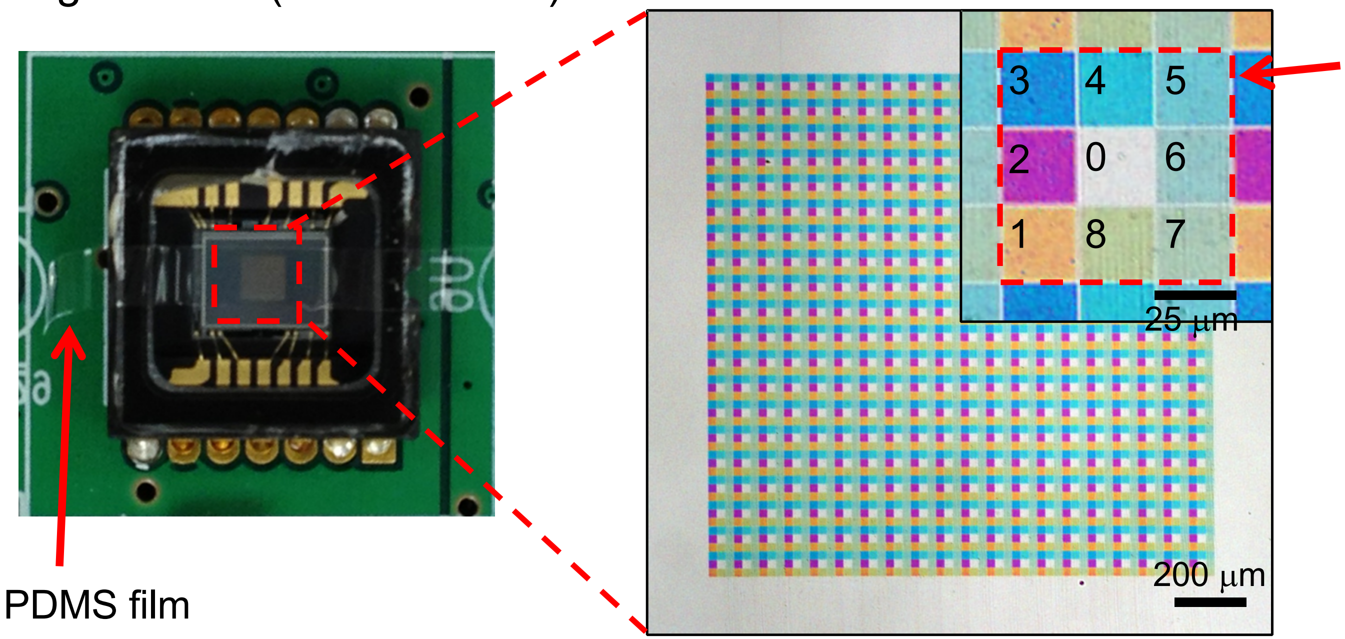
Multispectral imaging with PDMS-embedded Si nanowires



Park & Crozier, APL **101**, 193107 (2012)

Multispectral filter on CCD image sensor (monochrome)

Multispectral filter array: PDMS film embedded with nanowires

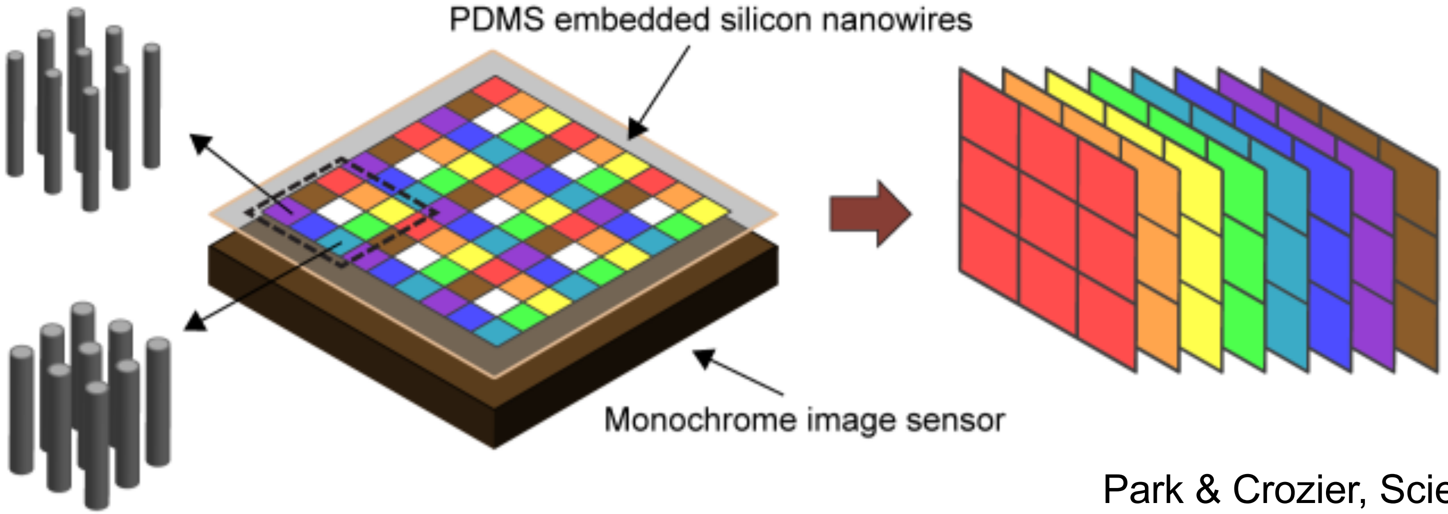


Unit cell:

- Region 0: no nanowires
- Regions 1-8: nanowires with radii from 45 to 80 nm
- Nanowires: 1.7 μm long, 1 μm pitch
- Overall extent: 75×75 μm

Filter array: 20 × 20 unit cells

Multispectral imaging with PDMS-embedded Si nanowires



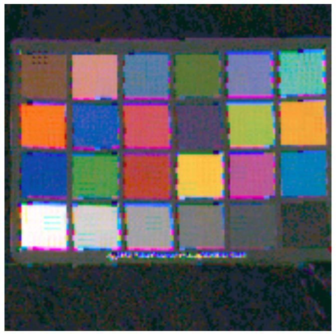
- 3 visible channels (RGB)
- 5 near-infrared (NIR) channels

Park & Crozier, Scientific Reports 3, 2460 (2013)

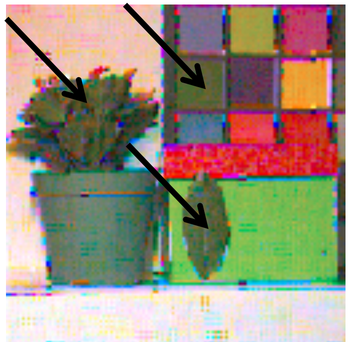
Color images

Resistors

Color checker card

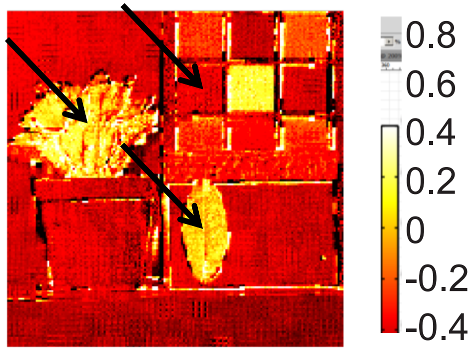


Plant, leaf & colour checker card



Normalized difference vegetation index image

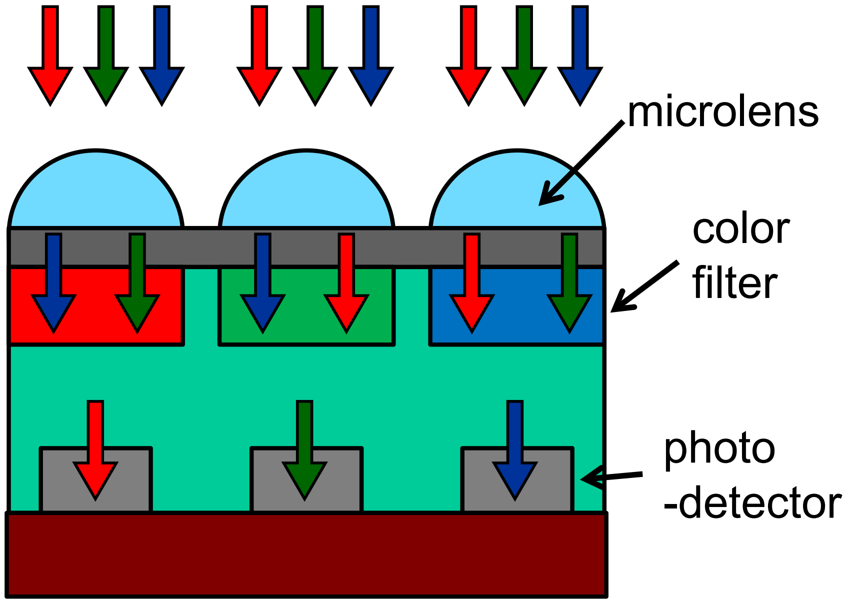
$NDVI = (NIR - VIS)/(NIR + VIS)$



We demonstrated multispectral imaging (3 VIS & 5 NIR channels) with our PMDS-embedded nanowire filter array mounted on a black & white image sensor

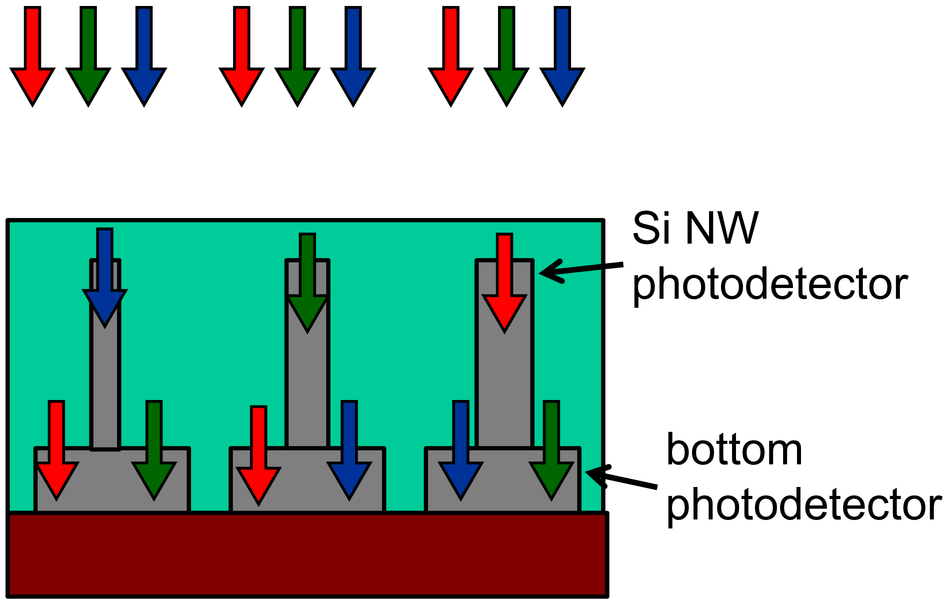
Toward nanowire-based image sensors

Conventional image sensors



•Colour separations performed using absorptive color filters & de-mosaicking
•Primary color RGB filters transmit red, green and blue light
•This limits efficiency, because much of spectrum is blocked, e.g. red & blue for green filter

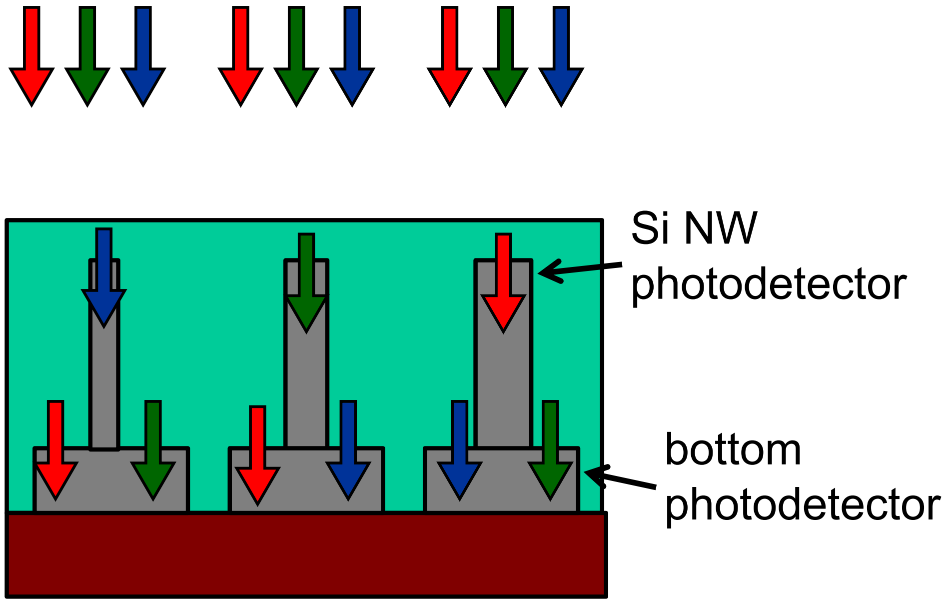
Proposed nanowire-based image sensor



•Part of spectrum absorbed by Si NW & converted to photocurrent
•Remaining part of spectrum absorbed by planar photodetector, & again converted to photocurrent
•By choosing NW radius, pixels with different spectral responses obtained.

Toward nanowire-based image sensors

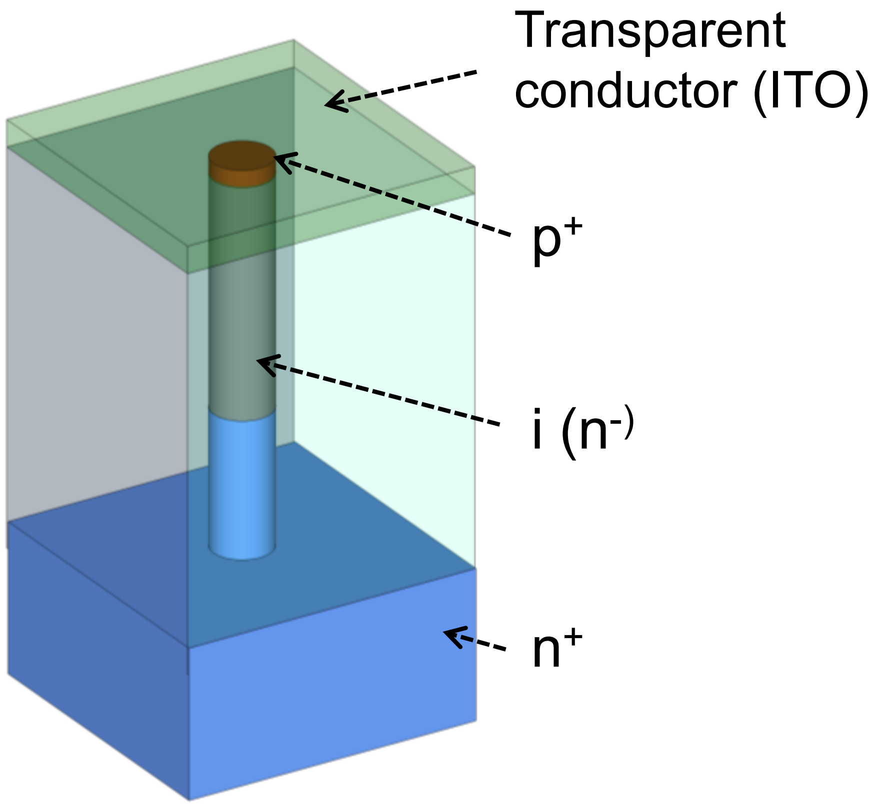
Proposed nanowire-based image sensor



•Our goal: image sensor pixel with

photodetector 1: in NW
photodetector 2: below NW (in substrate)

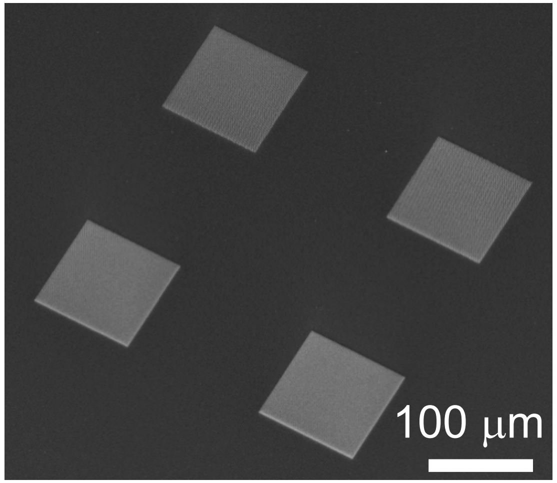
Nanowire photodetector pixels



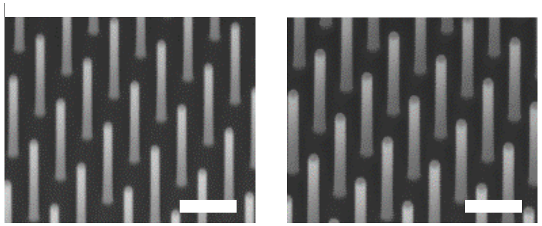
•Arrays of nanowires (10,000 per array)
•Each nanowire contains a vertical P-I-N photodetector

Fabrication result

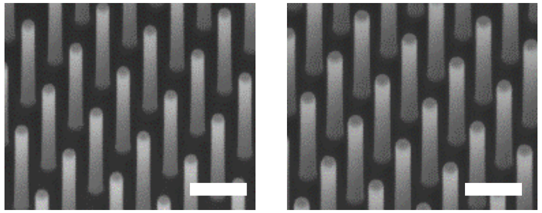
After dry etch



R=80 nm R=100 nm

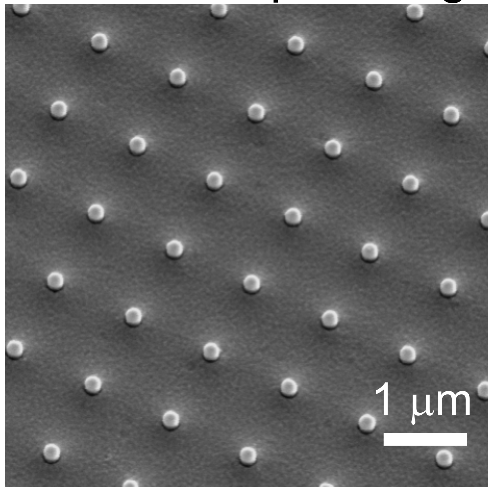


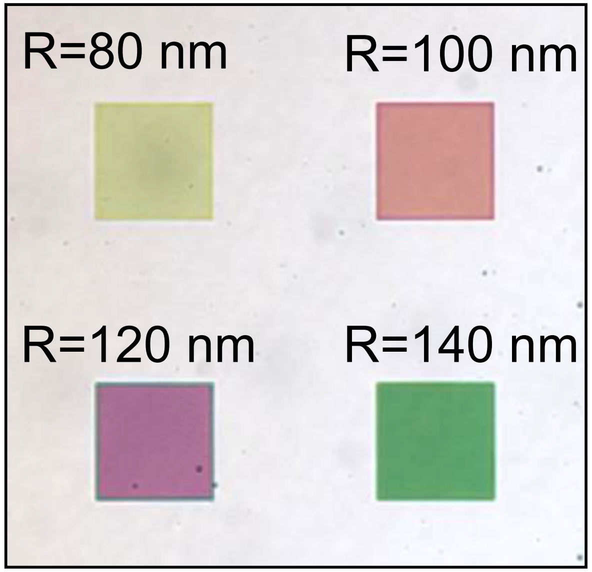
R=120 nm R=140 nm



1 μm

After ITO sputtering

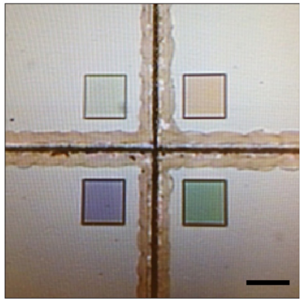




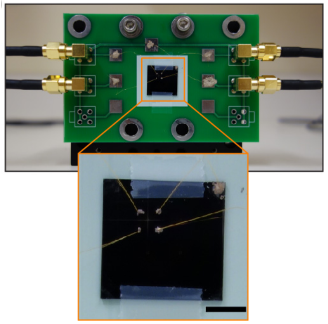
- We fabricated square arrays of nanowires with radii (R) from 80 to 140 nm
- Nanowires are 2.7 μm long, on a 1 μm pitch.
- Overall array extent: 100 × 100 μm

Color imaging with NW photodetectors & no filters

- Scribe for electrical isolation



- Mount on printed circuit board (PCB)



•Illuminate test scene with lamps

•Image with SLR lens (f=50 mm)

•Raster scan NW photodiodes at image plane (180 × 128 positions)

R=80 nm

R =100 nm

R=120 nm

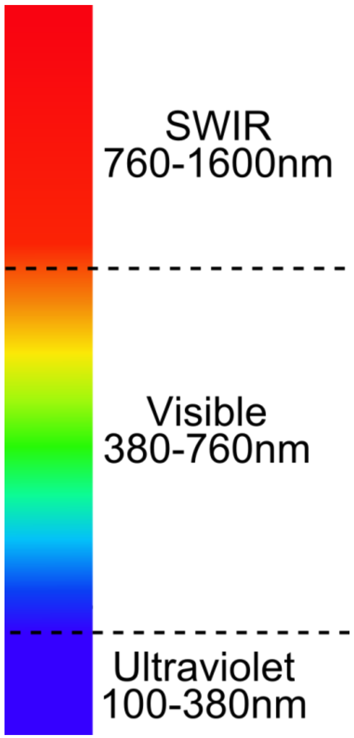
R=140 nm

End results

Park, Dan, Seo, Yu, Duane, Wober, Crozier, Nano Letters (2014)

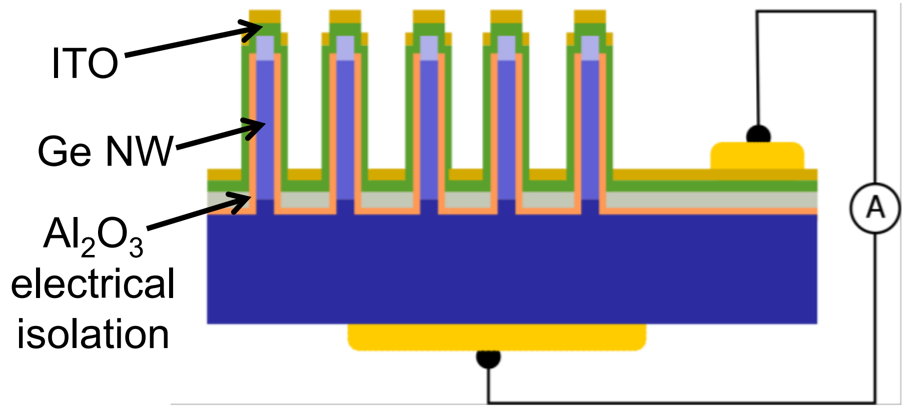
Germanium nanowires: extension to shortwave IR

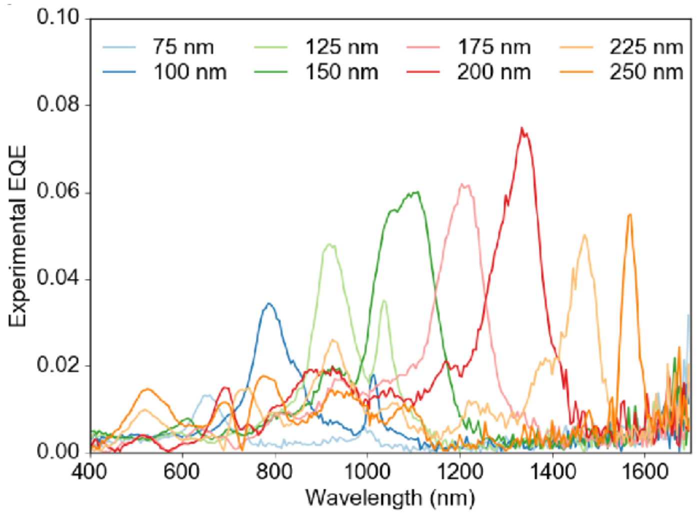
- **Why shortwave infrared ?**
  - Wafer & solar cell inspection
  - Military surveillance
    - Imaging in haze & fog
    - Target recognition
  - Multispectral imaging



http://www.sensorsinc.com

On-going work:Ge nanowires





Solanki et al, accepted for *ACS Photonics*

•We demonstrate vertical Ge NWs as narrowband photodetectors. Measured spectral response peaks are as narrow as 40 nm & can be shifted from visible to infrared wavelengths

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Recent years have seen huge increase in prevalence of imaging systems, largely driven by sales of smartphones. This can be expected to continue, with demand for new functionalities (e.g. multispectral imaging). Nano-optics could be an enabling technology to allow these functionalities to be achieved in smaller & smaller platforms.

Summary

Multispectral imaging using semiconductor nanowire photodetectors

-waveguiding properties of vertical silicon nanowires can be harnessed for spectrally-selective absorption, thereby enabling multispectral imaging

Previous funding (this work)

NSF

ECCS-0747560
ECCS-120168
ECCS-130756

DARPA

N66001-10-1-4008
W911NF-13-2-0015

ZENA TECHNOLOGIES

center for excitonics

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veski

DARPA

HR001-16-1-0004