This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2019-4474C

Fullerene-Sensitized Carbon Nanotube Array Phototransistor with Responsivity of 10^8 A/W

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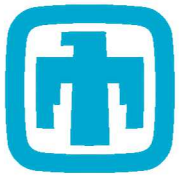
Sandia National Laboratories, Livermore, CA



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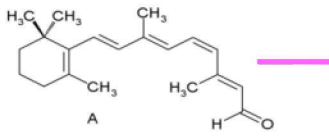
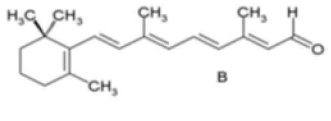
Overview

- **Background**
  - Motivation
  - Device operation
- **Photoresponse**
  - Steady-state
  - Pulsed
  - Low-light
- **Modeling**
  - Scattering
  - Three-state system
- **Conclusions**

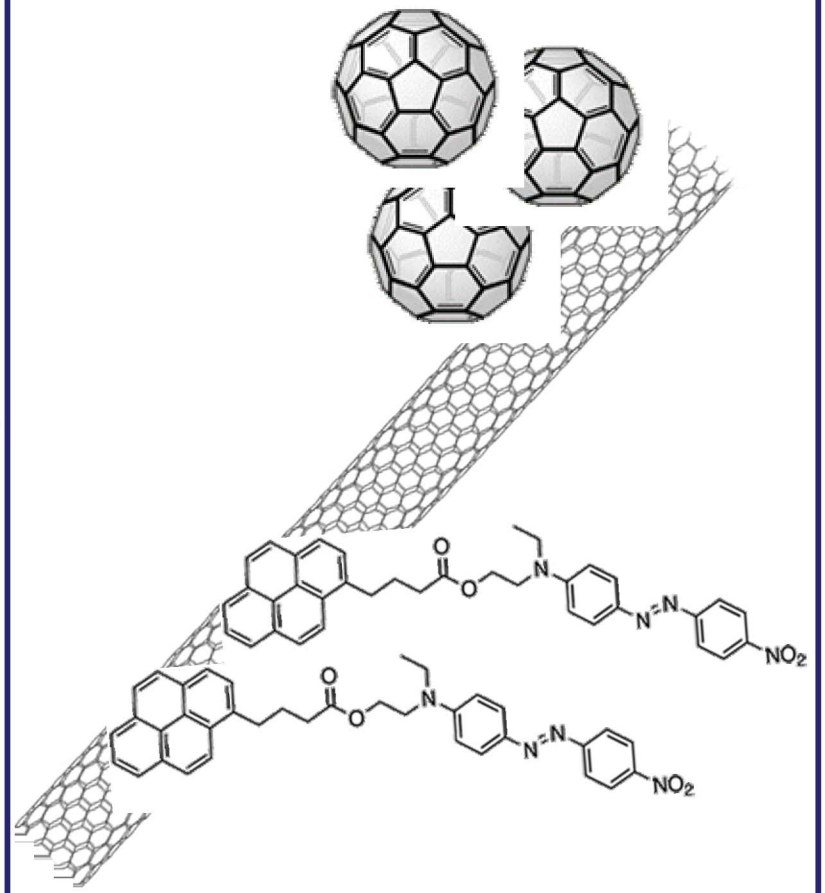
Q: Can we mimic (and improve) retinas?

Retinal molecule

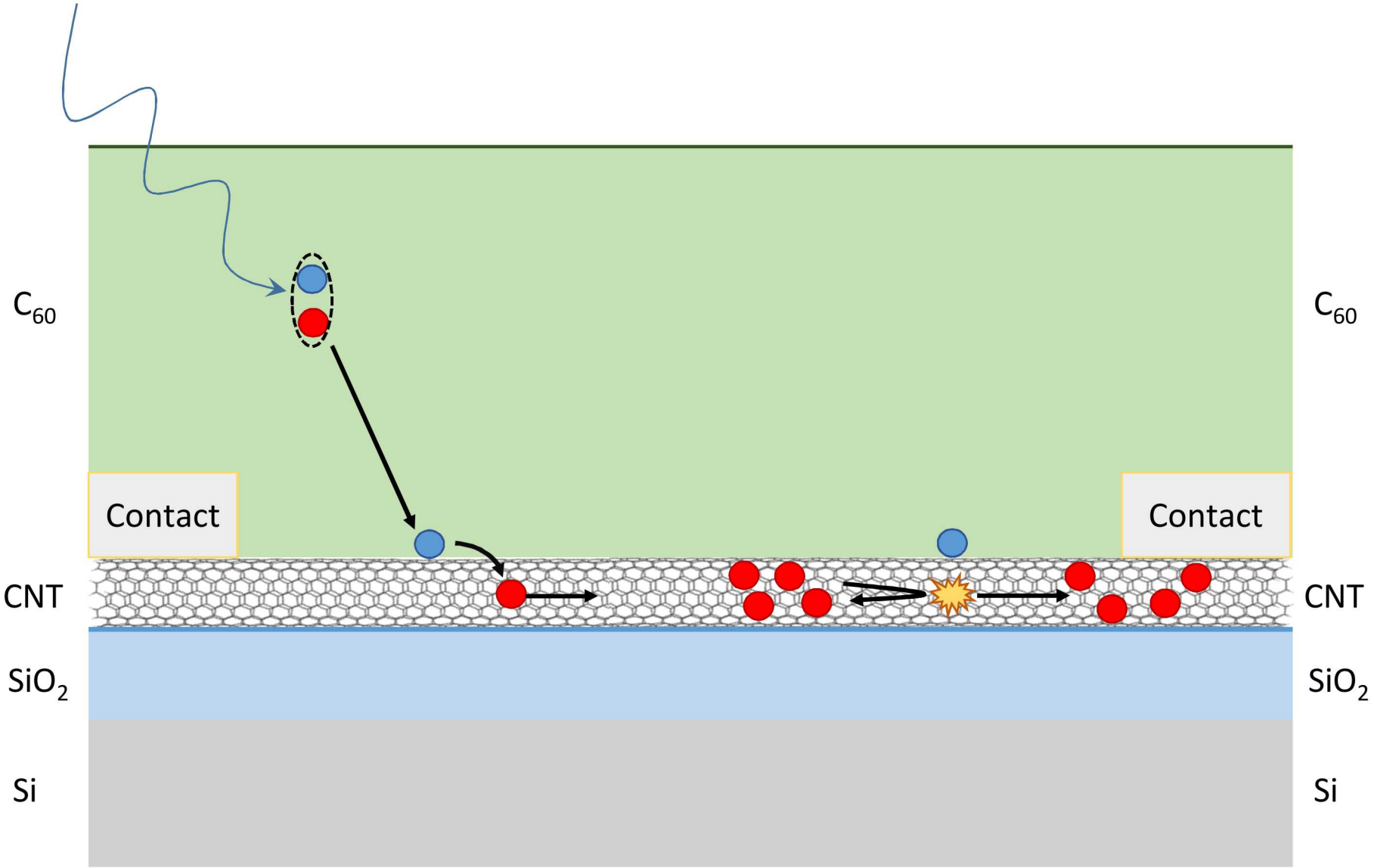




Cis *Trans*

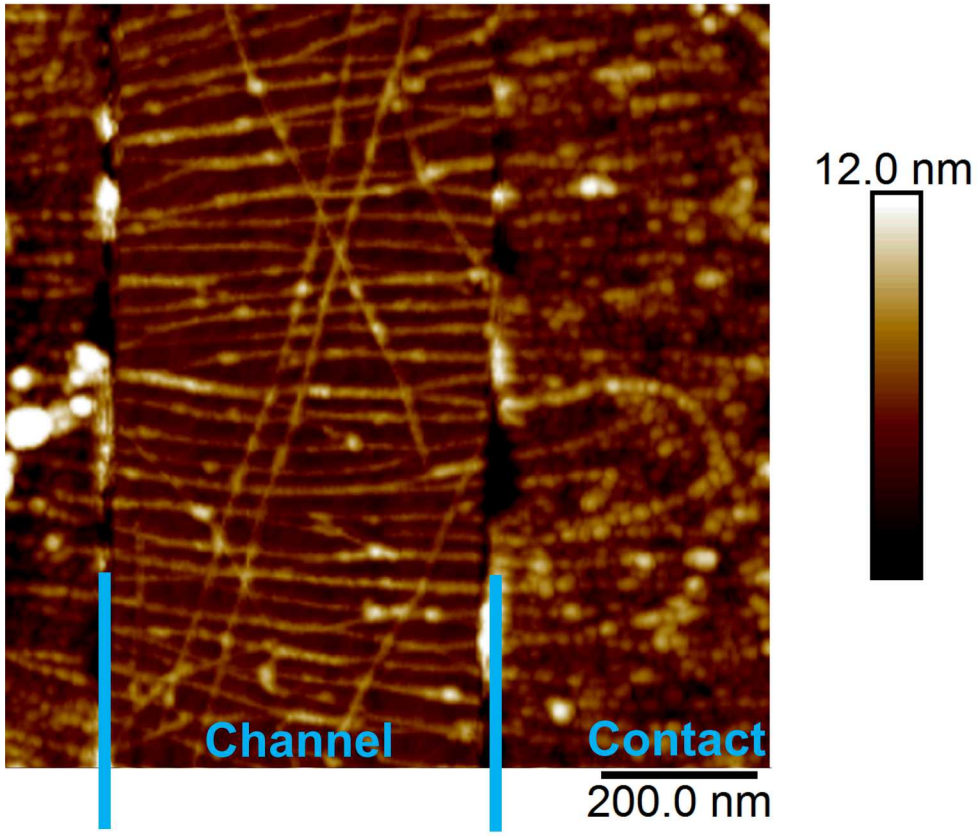


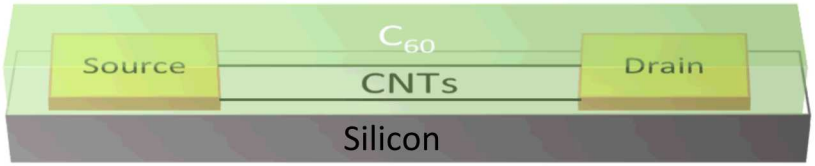
Device Operation



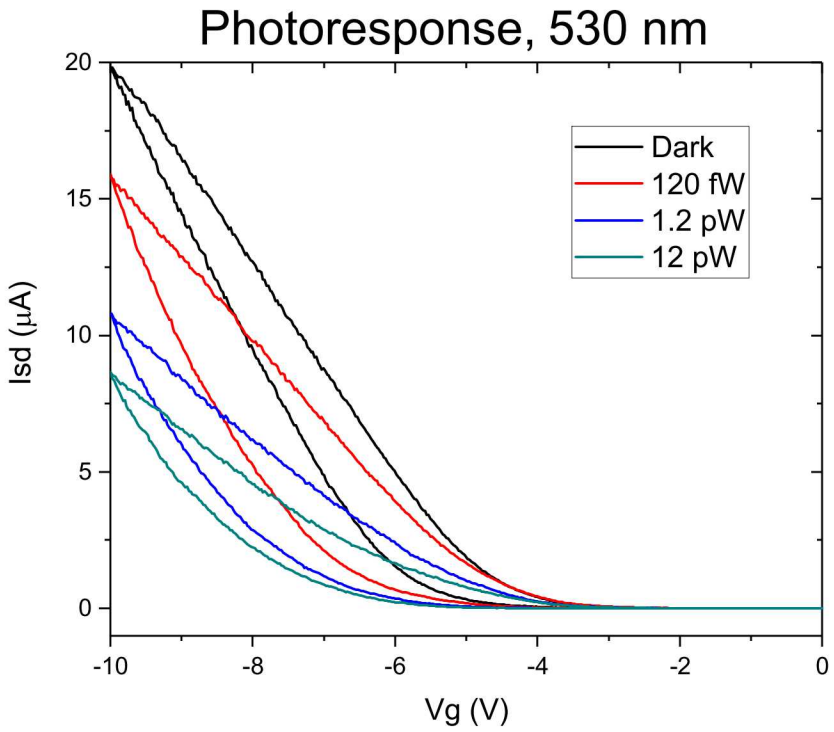
Aligned nanotube devices

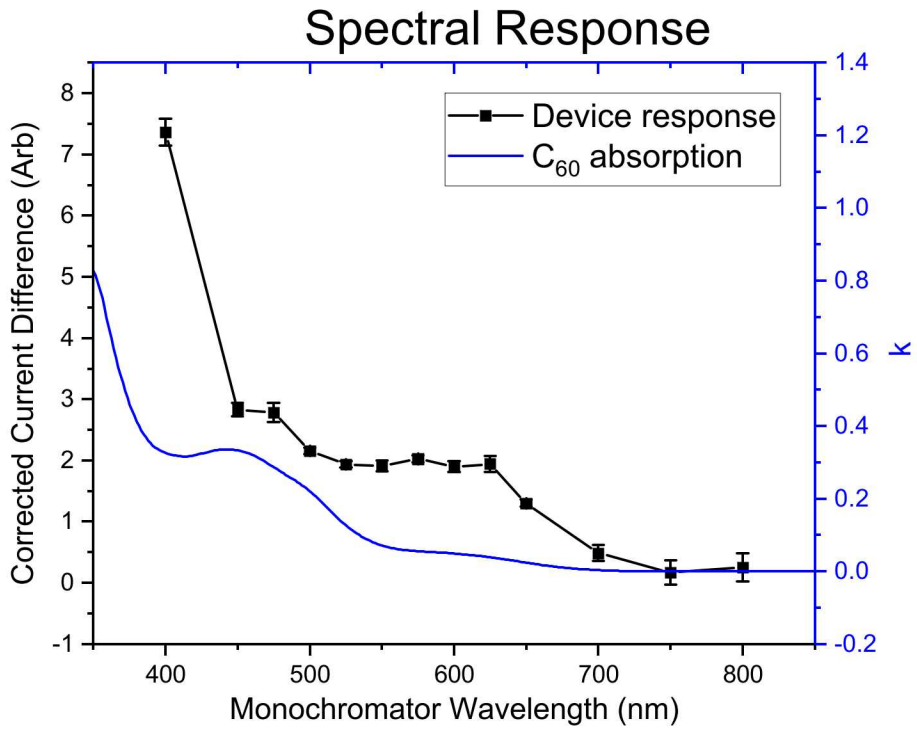
- **Carbonics ZEBRA wafer**
  - 99.9% semiconducting CNT
  - 40-60 CNTs/micron
  - Diameter: 1.3 -1.7 nm
  - CNT length: 400 nm(mean)
- **Transistors**
  - Width: 5 – 80 µm
  - Length: 70 nm – 8 µm
  - Device area: channel length x channel width
- **Sensitizer**
  - 40 nm C_{60}



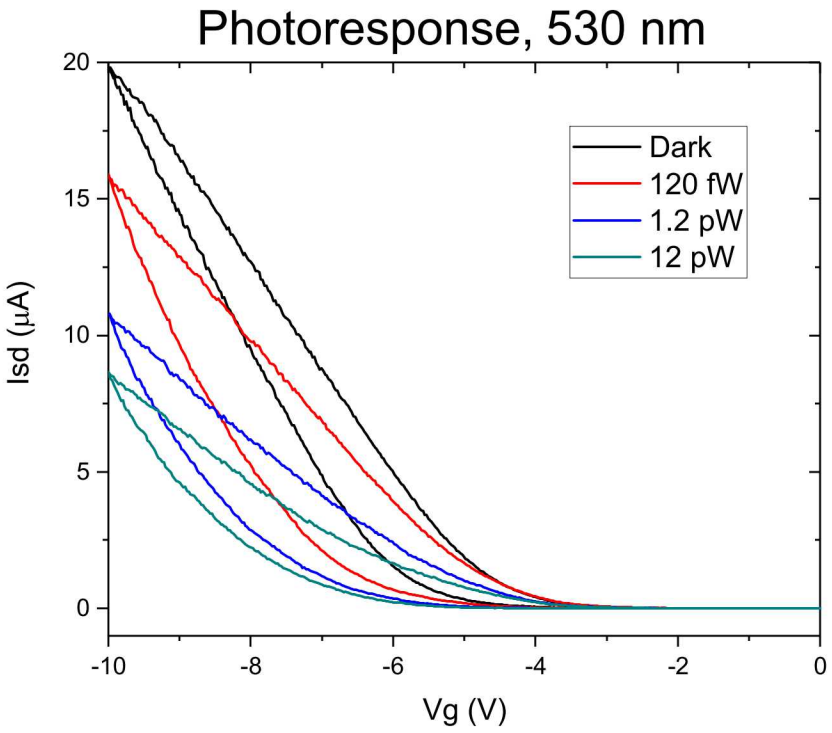


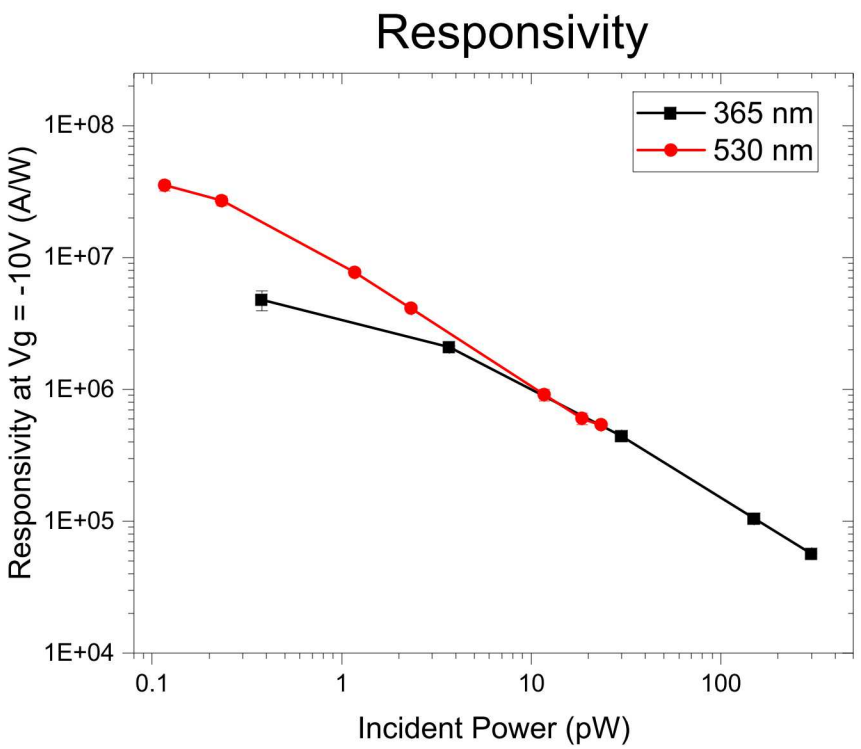
Photoresponse





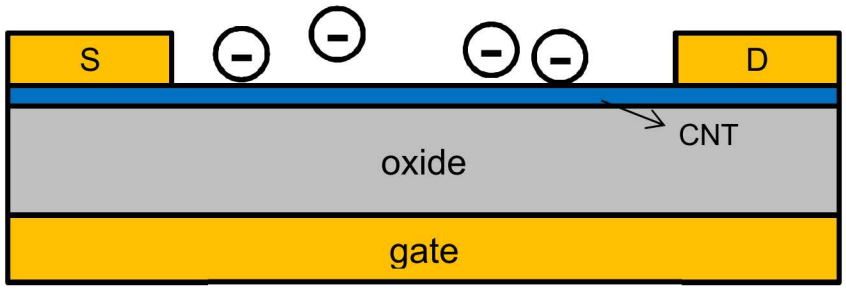
Photoresponse





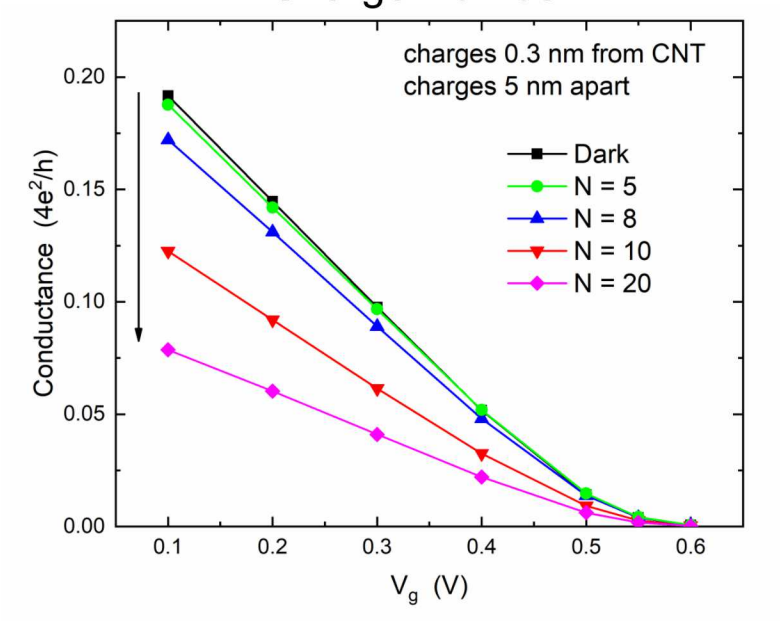
- Responsivity > 10^7 A/W
- Gain > 10^8
- Sensitive to UV and visible

Detection mechanism

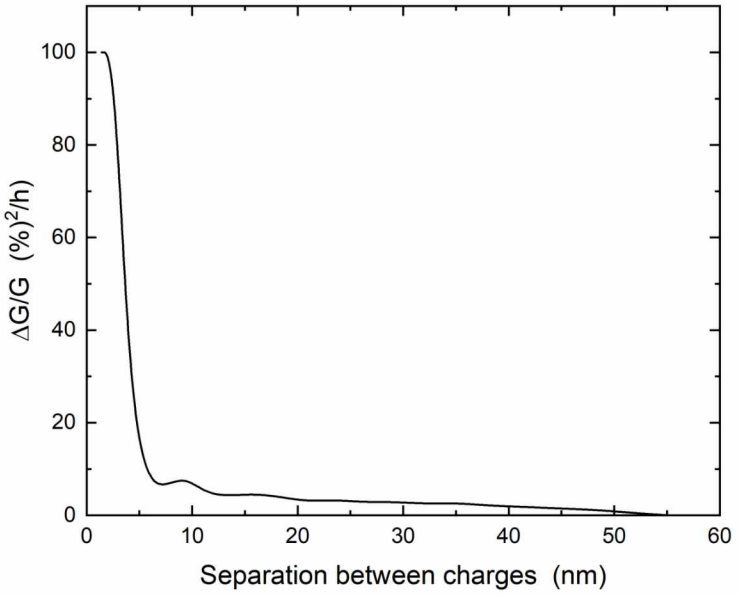


NEGF simulation

Charge Number



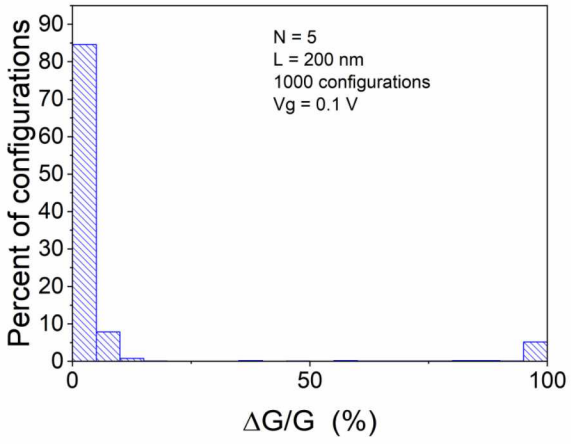
Charge Separation

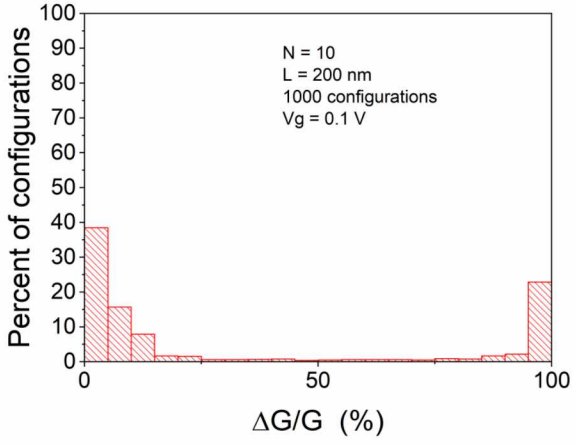


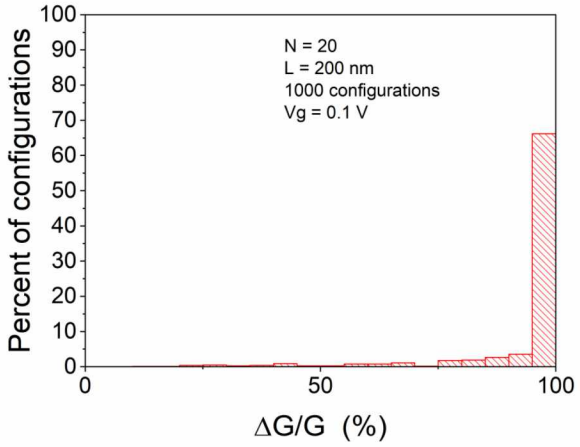
Current decrease due to scattering from charges on CNT

Detection mechanism

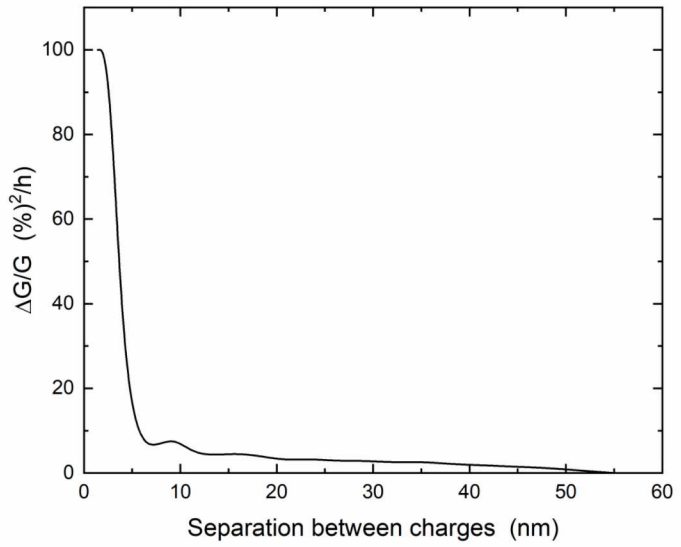
Charge Configuration Simulations



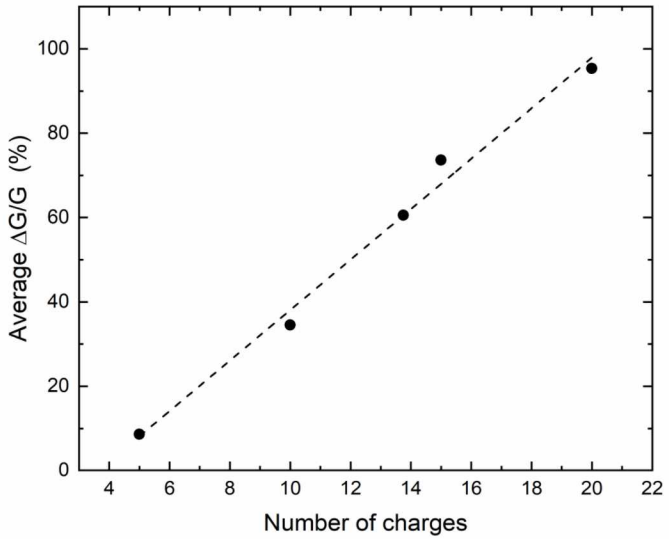




Charge Separation

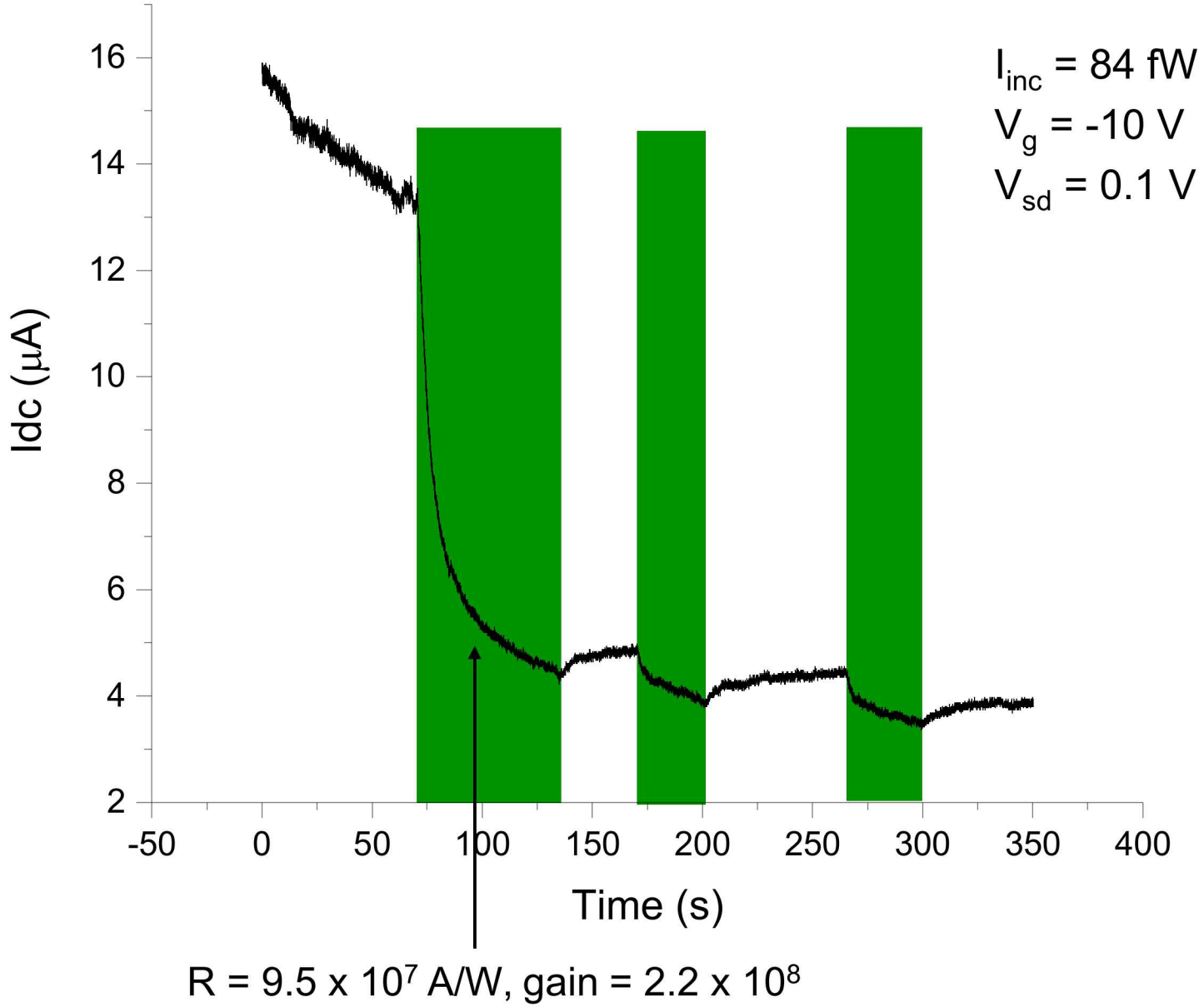


Average Change

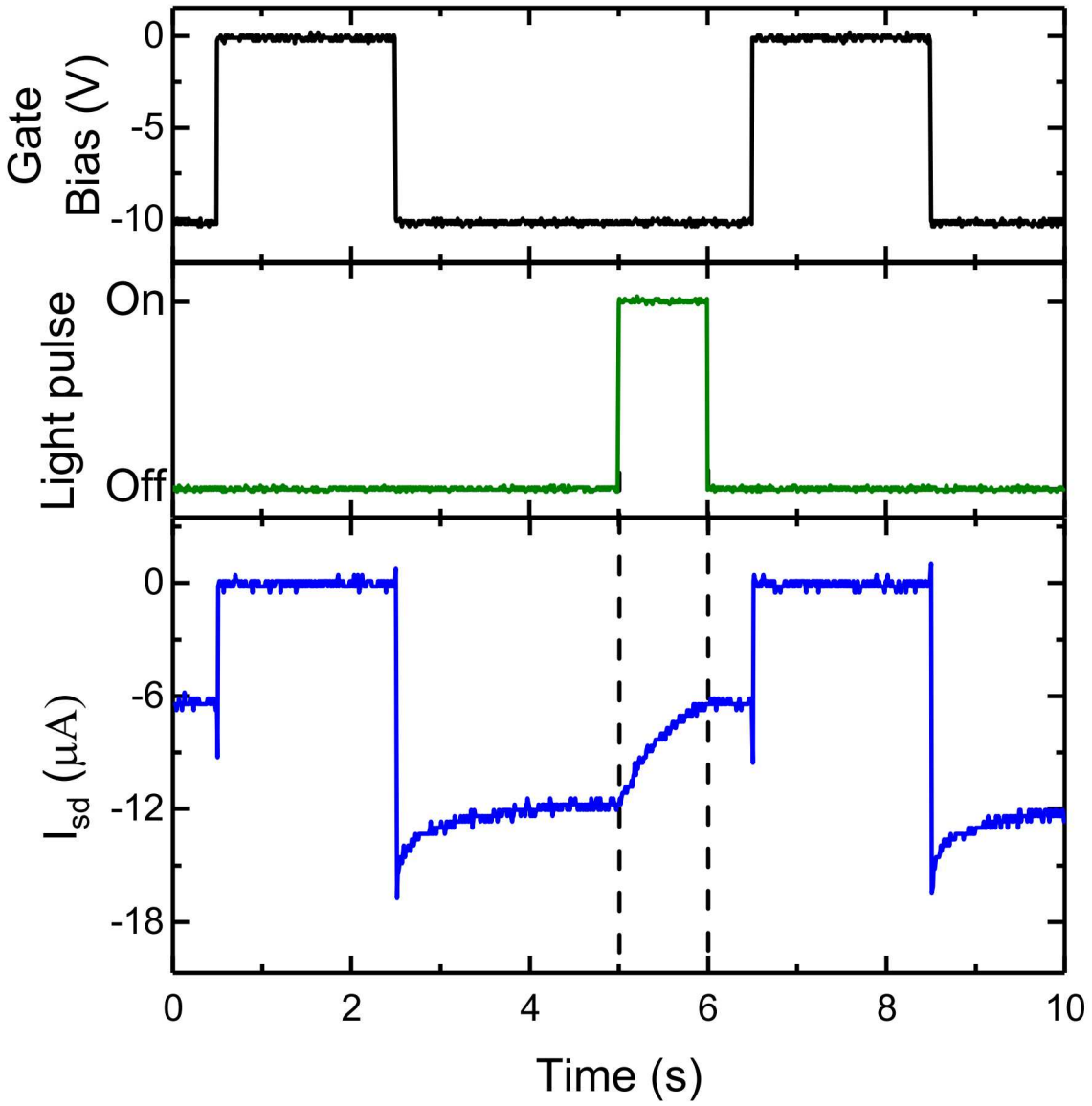


Conductance linearly dependent on # of charges

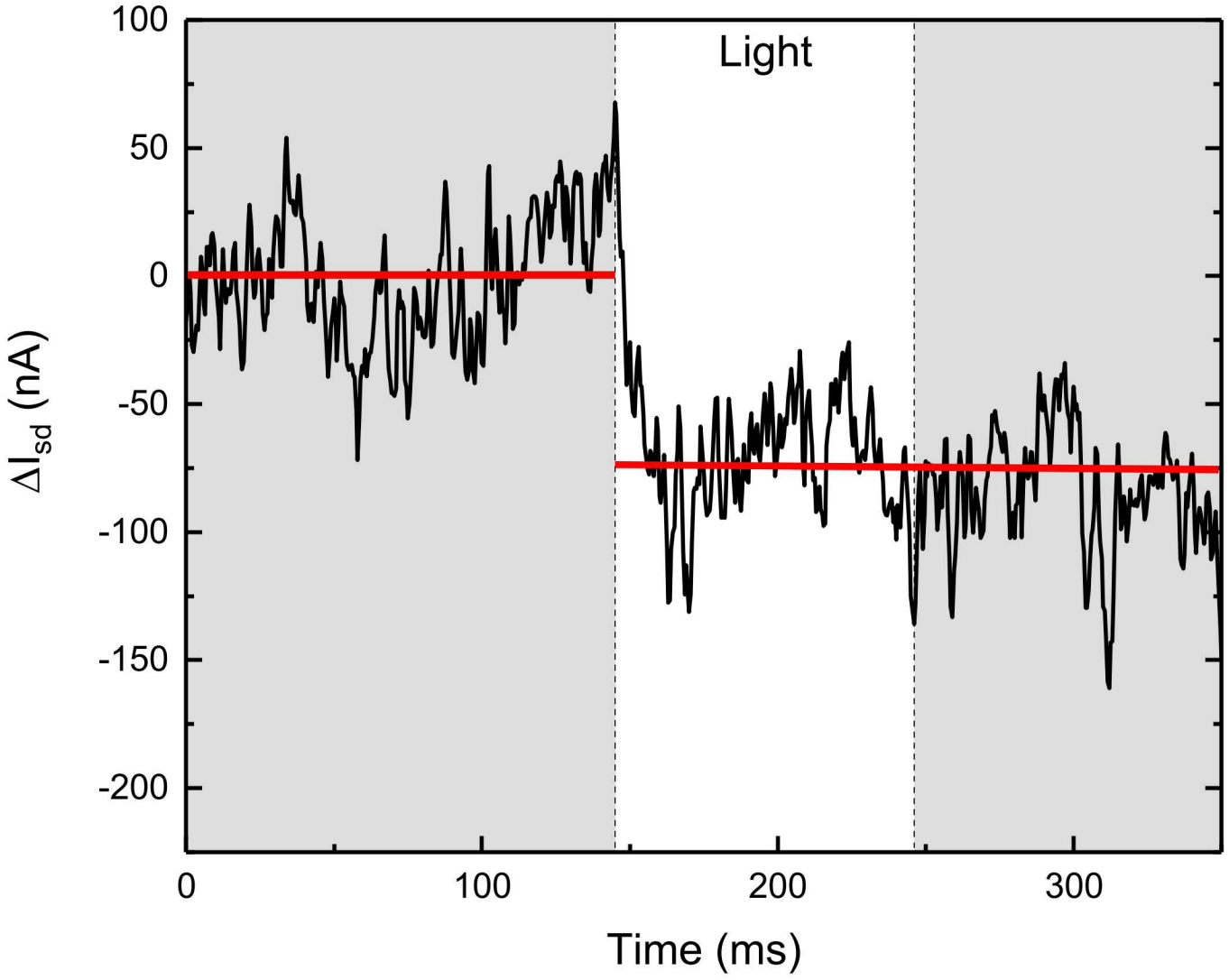
Time response



Pulsed Vg

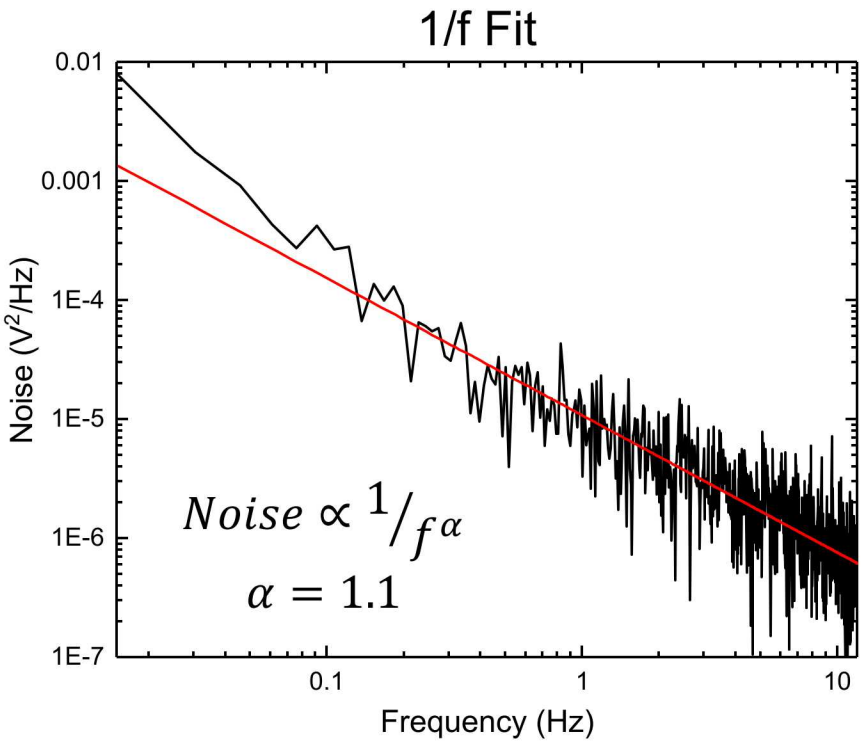

Gate Bias (V)
0
-5
-10
Light pulse
On
Off
I_{sd} (μA)
0
-6
-12
-18
0
2
4
6
8
10
Time (s)

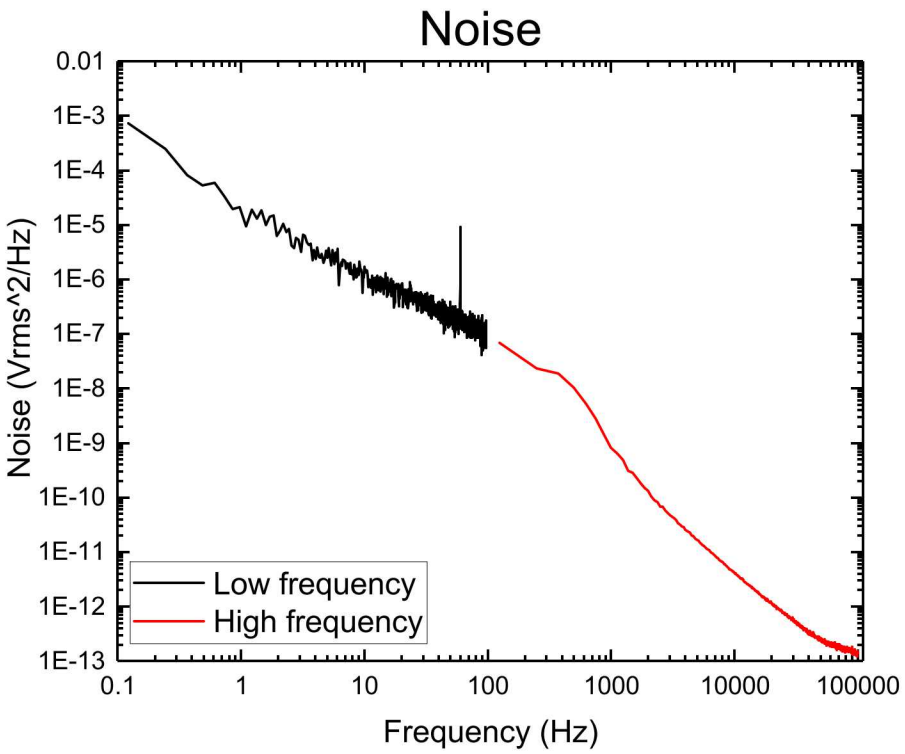
Pulse Response



Pulse contained 5e4 photons, corresponding to 50-80 photons per CNT

Device Noise

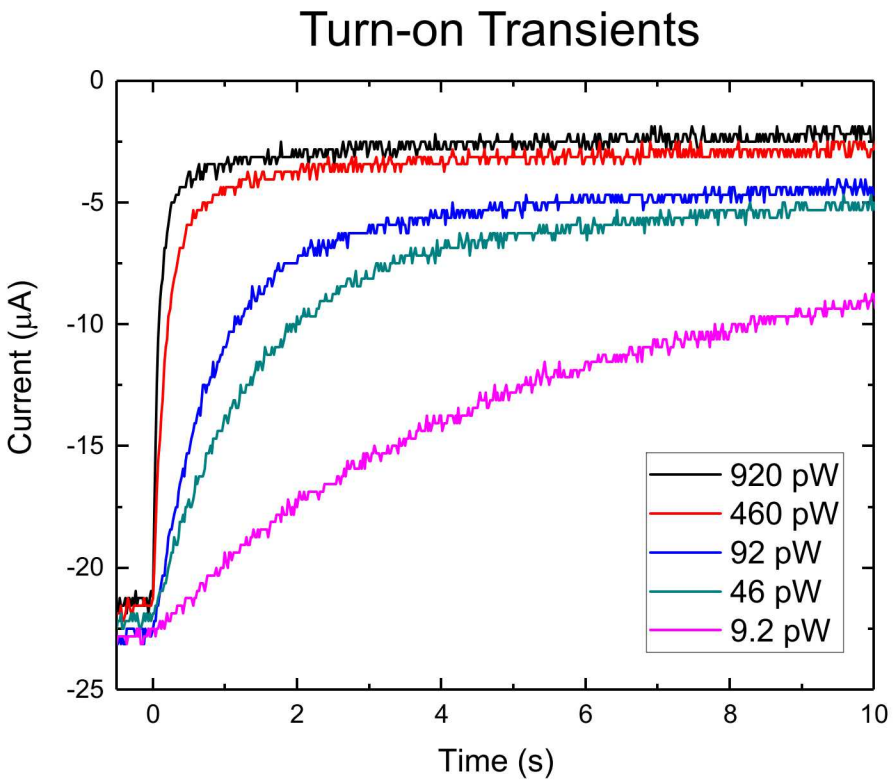


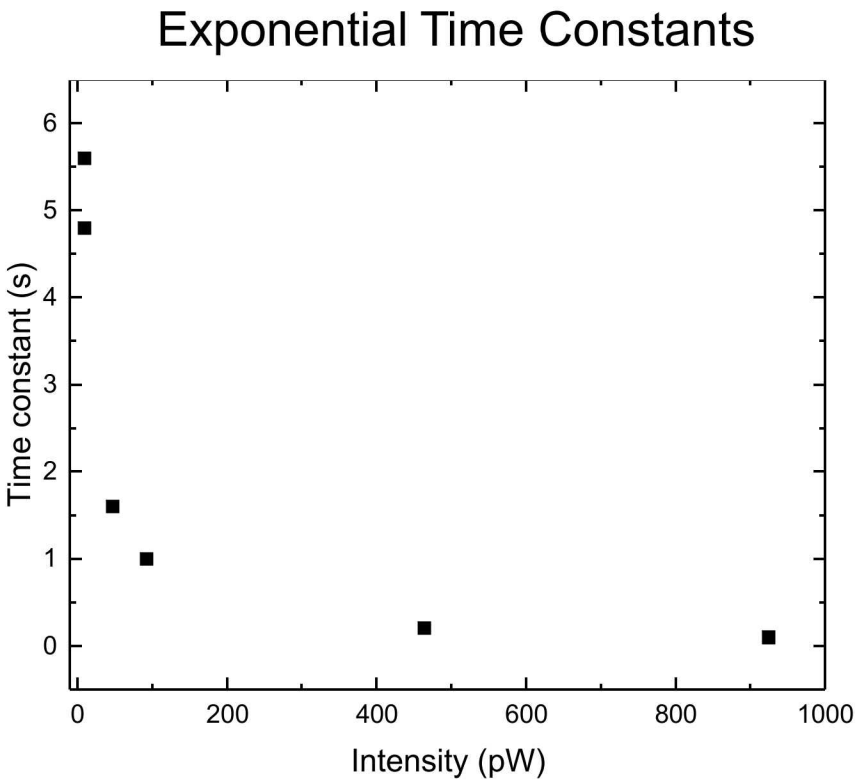


$NEP = 3.3 \cdot 10^{-15}$ W/√Hz

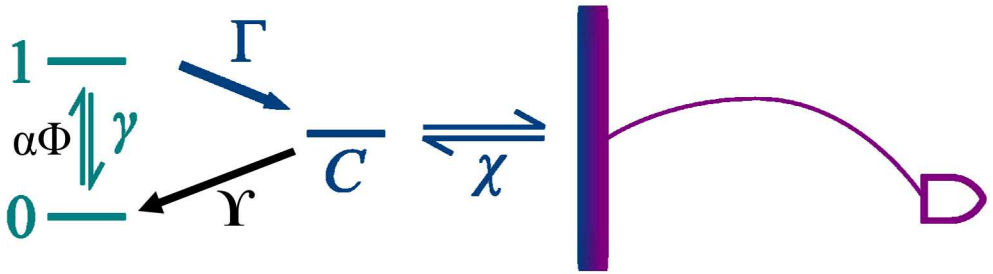
$D^* = 1.5 \cdot 10^{11}$ Jones

Intensity Dependence





Photodetection Process



α = Photoabsorption efficiency
Φ = Light intensity
Γ, Υ = Rate constants
C = Trap state at CNT interface
χ = Detection efficiency

From continuum rate equations, and assuming Γ is fast,

Population of C state:

$$n_c(t) \approx \frac{\alpha\Phi}{\Upsilon + \alpha\Phi}\left\{1 - \exp\left[-\left(\Upsilon + \alpha\Phi\right)t\right]\right\}$$

Bandwidth:

$$\frac{1}{\tau} = \Upsilon + \alpha\Phi$$

Steady-state population:

$$n_c\left(t \to \infty\right) = \frac{\alpha\Phi}{\Upsilon + \alpha\Phi}$$

Change in device current:

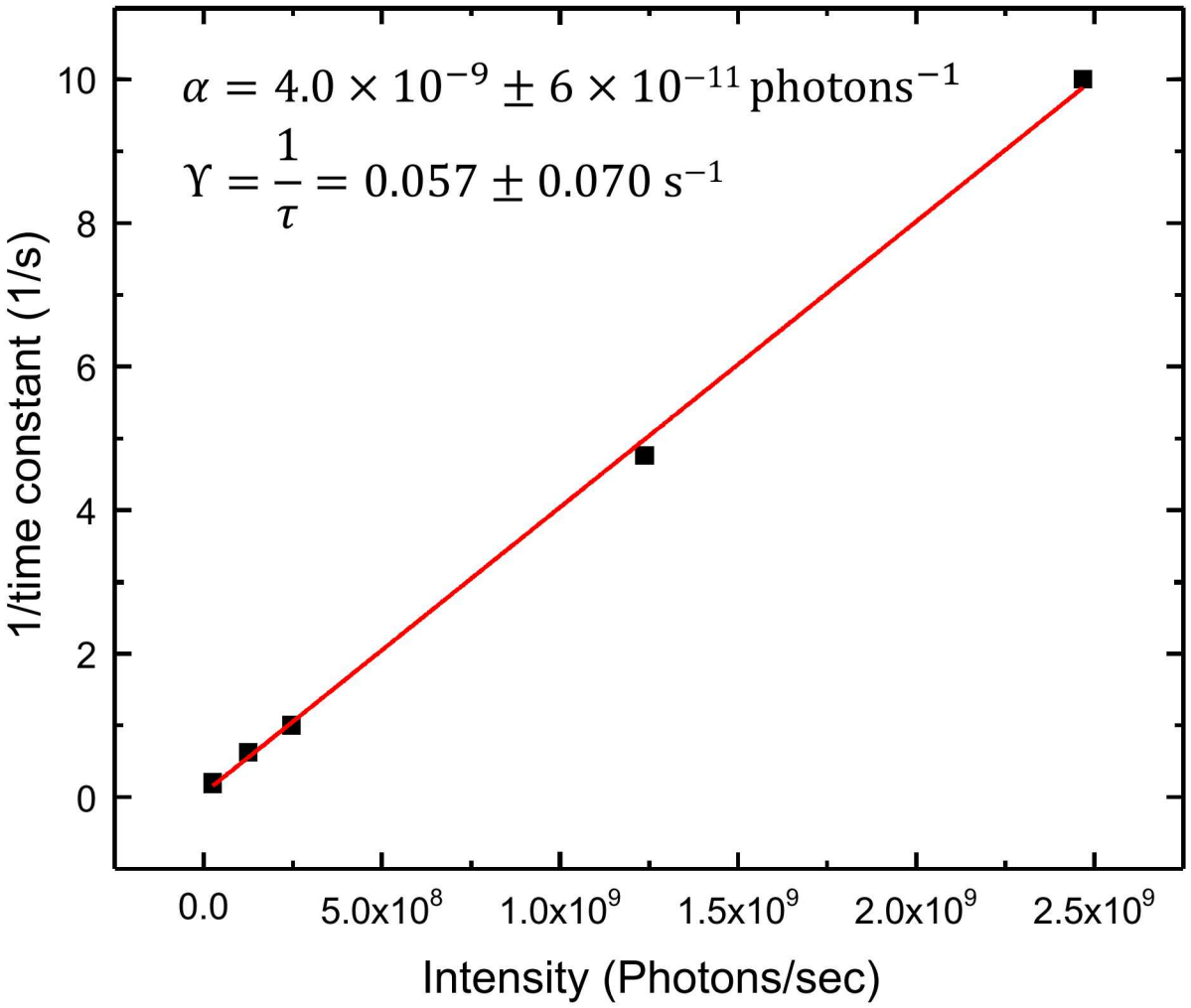
$$I(t) = \chi n_c(t)$$

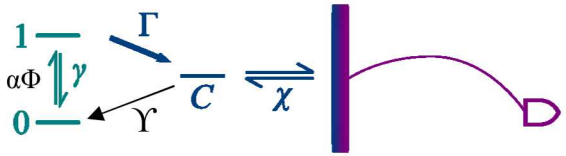
Steady-state responsivity:

$$R = \frac{I(t \to \infty)}{\Phi} = \chi\left(\frac{\alpha}{\Upsilon + \alpha\Phi}\right) = \frac{\chi}{\Upsilon/\alpha + \Phi}$$

S. M. Young, M. Sarovar, F. Léonard, *Phys. Rev. A* **2018**, *97*, 033836

Time Constant Fit

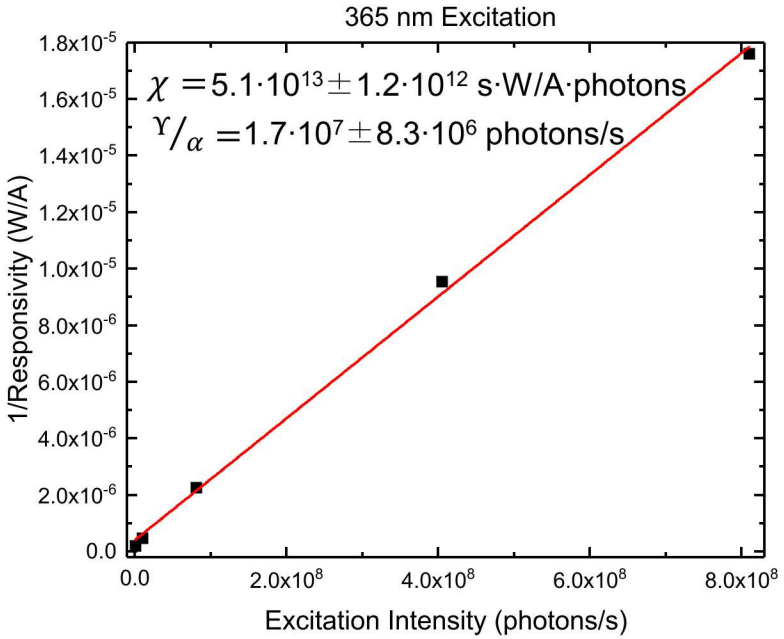


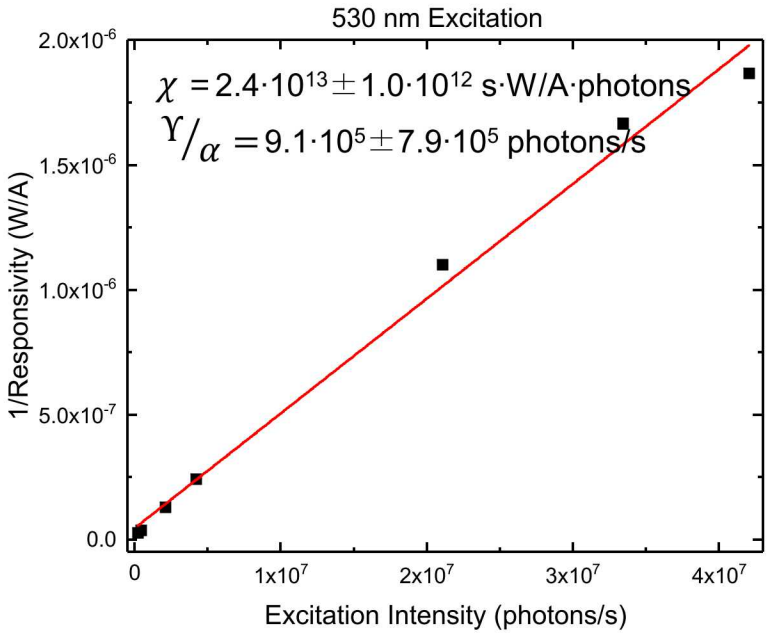


$$\frac{1}{\tau} = \Upsilon + \alpha\Phi$$

Validates physical model

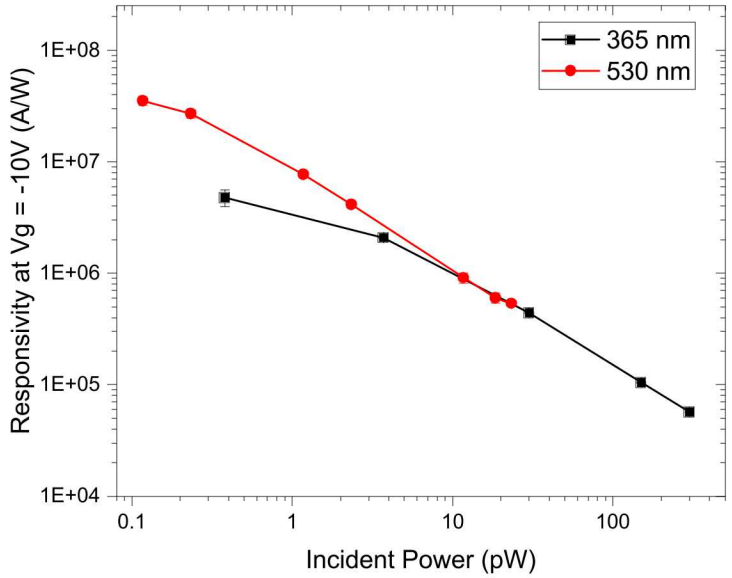
Responsivity Fits



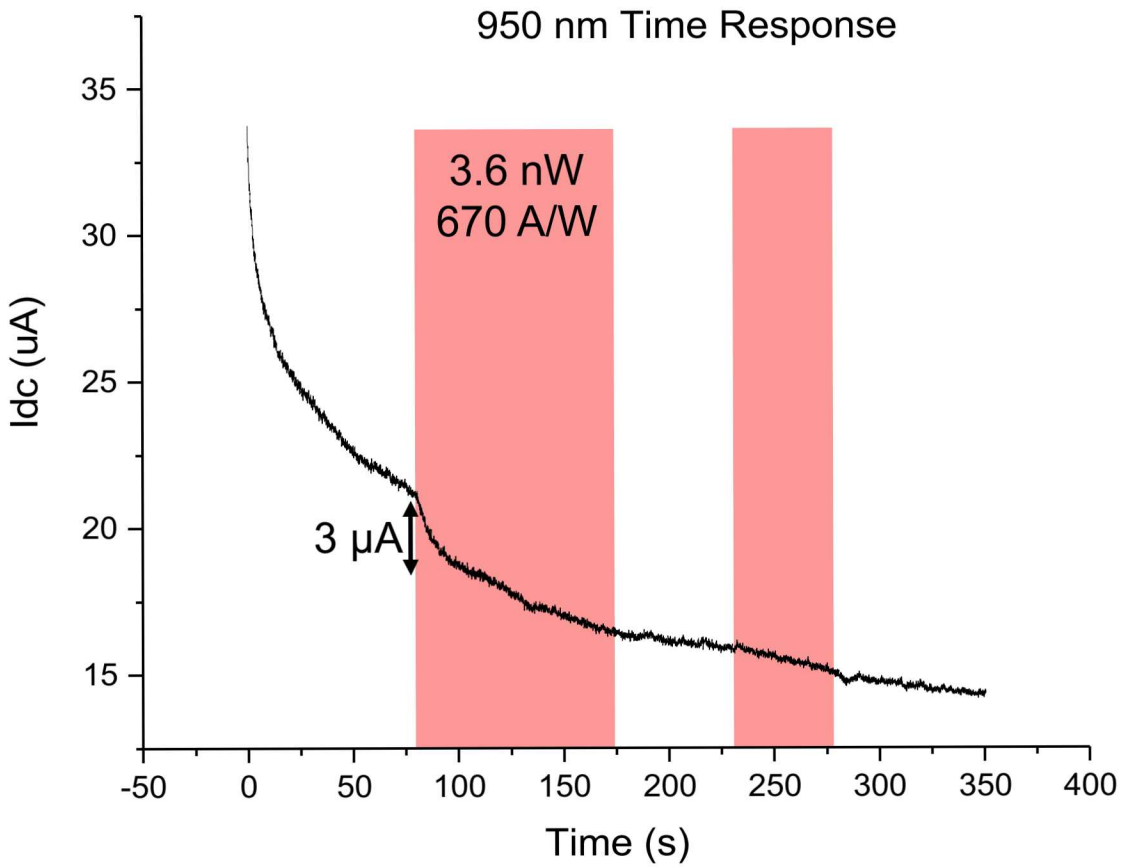


From time fits, $\Upsilon/\alpha = 1.6 \cdot 10^{7} \pm 2.1 \cdot 10^{7}$ photons/s

$$\frac{1}{R} = \frac{1}{\chi}\left(\frac{\Upsilon}{\alpha} + \Phi\right)$$

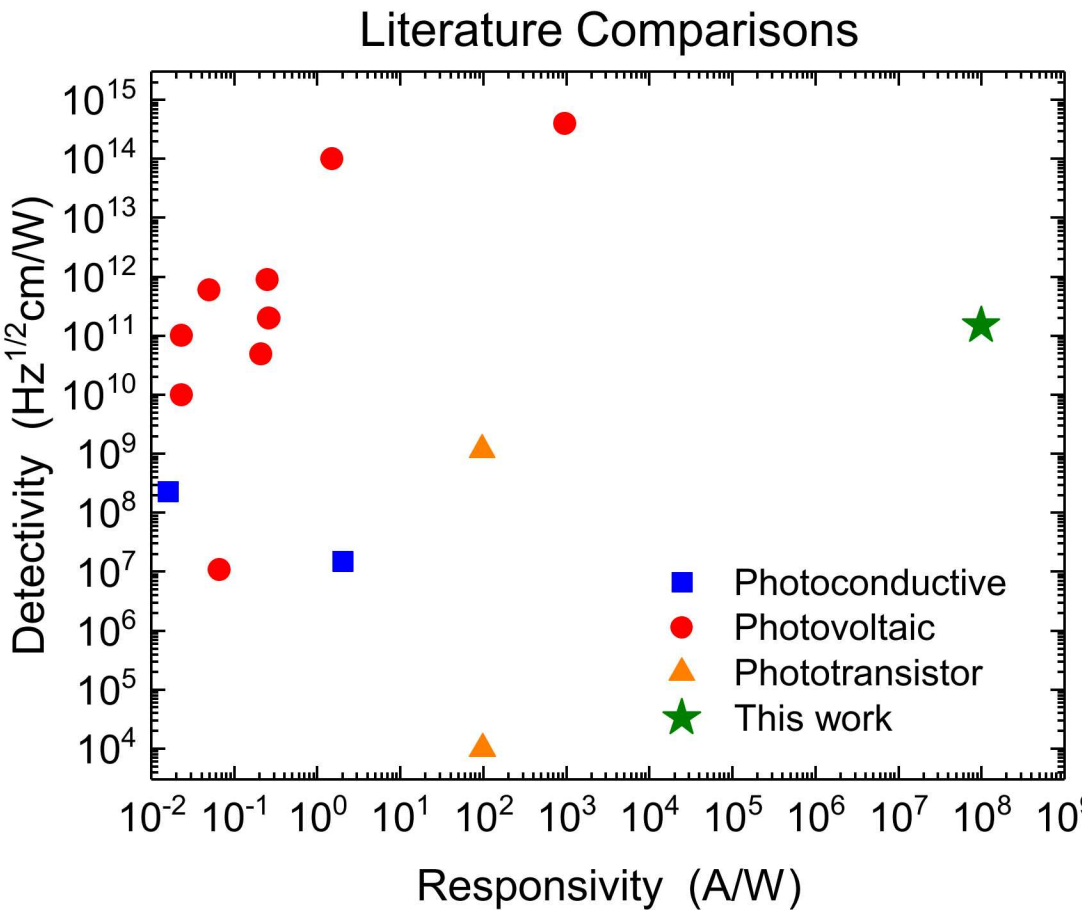


Multiband Response



Conclusions

- **Record responsivity**
- **Sensitive to visible, UV, IR**
- **50 photons/tube detected**



T.F. Zhang et al, *Scientific Reports* **2016**, *6*, 38569.
M. Salvato et al, *Nanotechnology* **2017**, *28*, 435201.
I. Hwang et al., *Nanoscale* **2017**, *9*, 16711.
K. Bergemann, F. Léonard, *Small* **2018**, *14*(42), 1802806.
X. He, F. Leonard, J. Kono, *Advanced Optical Materials* **2015**, *3*, 989.

Questions?

K. Bergemann, F. Léonard, *Small* **2018**, *14*(42), 1802806.

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This work was funded by the DARPA DETECT program.

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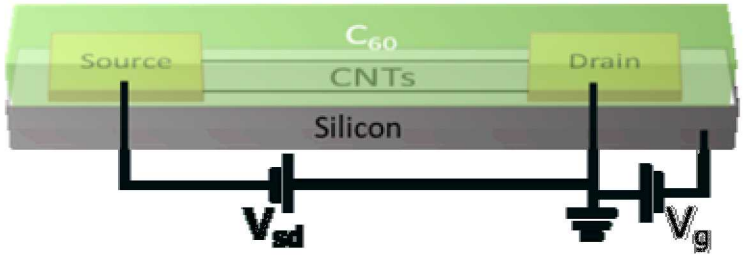
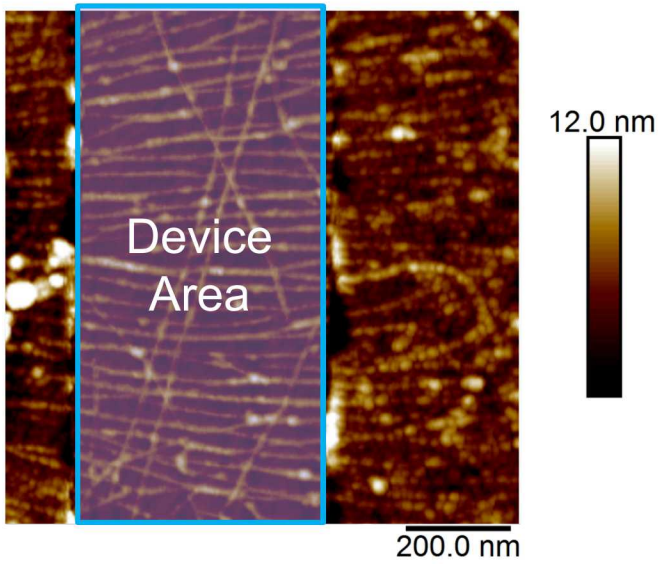
Device Testing

- **Transistors tested under vacuum**
  - Cryostat used as vacuum chamber
  - Room temperature
- **Illuminated through CaF_2 window**
  - 365, 530, 950 nm LEDs
  - Xenon lamp + monochromator
- **Back gate, front source and drain**



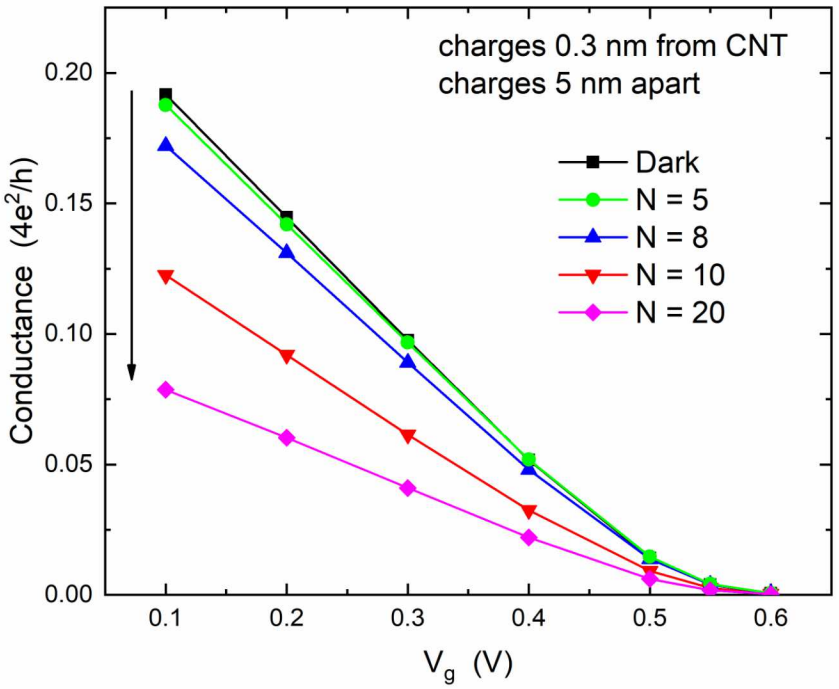


Simulation Details

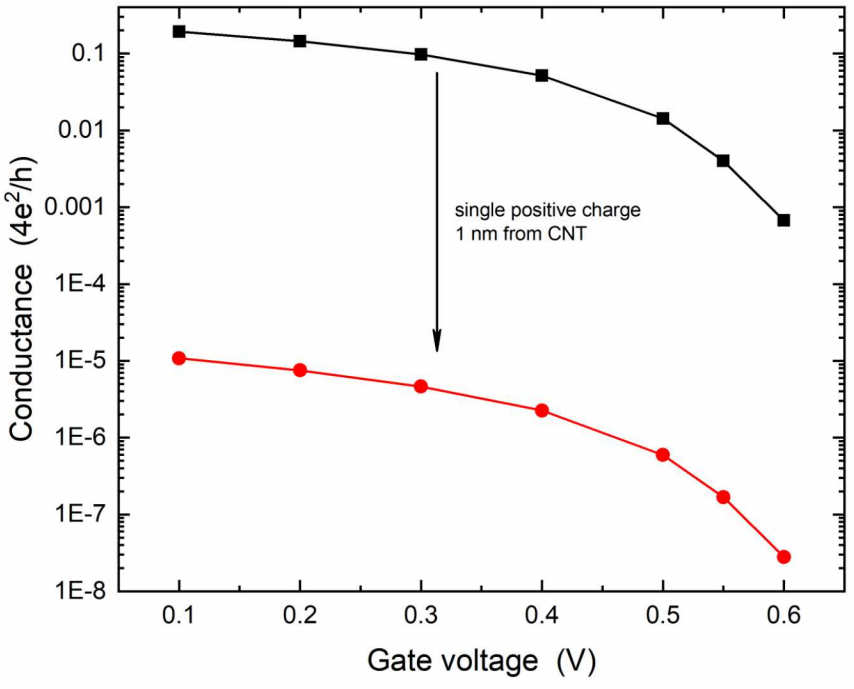
- **Non-equilibrium Green's function (NEGF) approach**
  - **Self-consistent calculations of conductance as function of gate voltage in presence of negative charges**
- **Random charge configurations**
  - **1 nm bins**
  - **One charge allowed per bin**

Donors vs Acceptors

Effect of Negative Charges

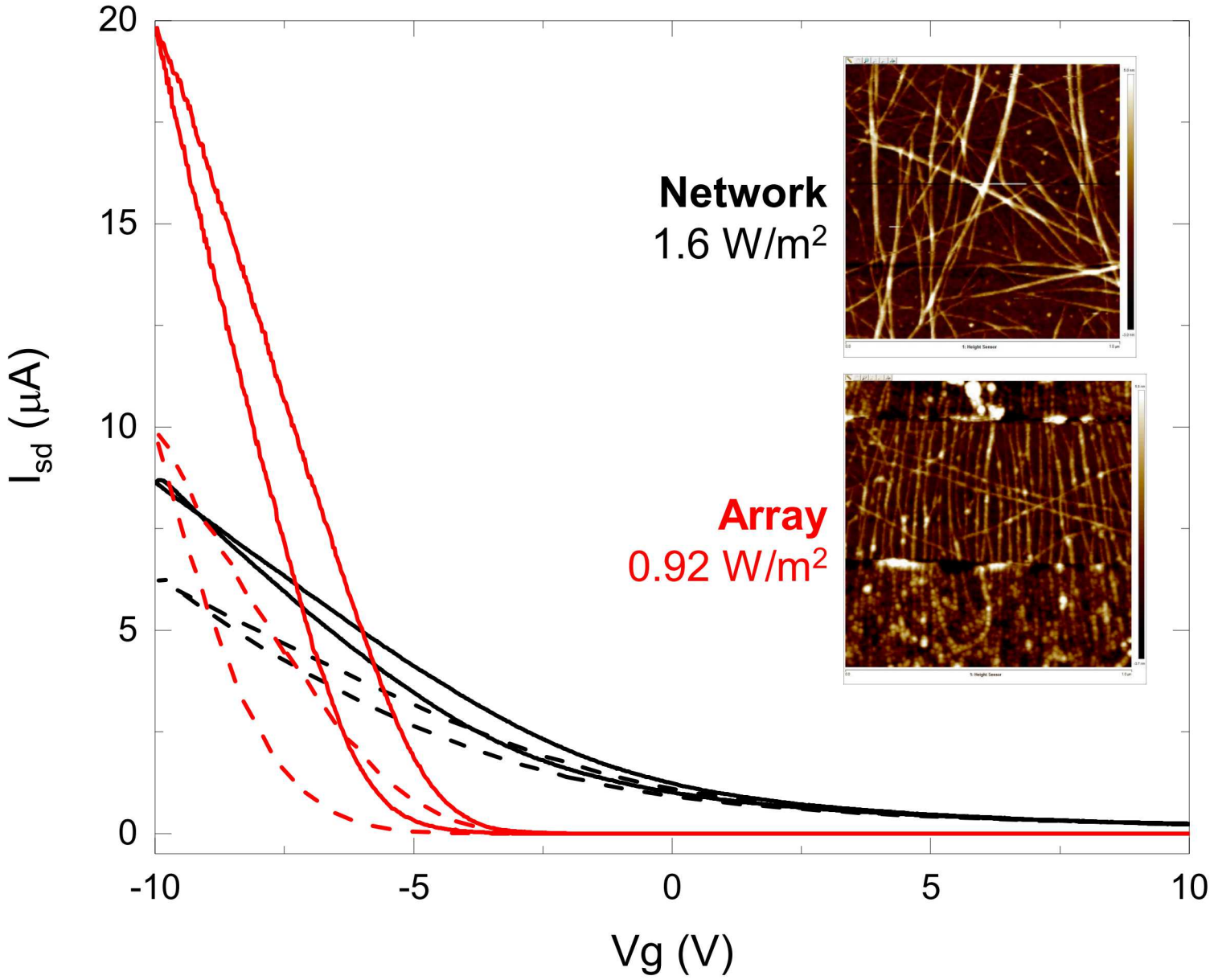


Effect of Positive Charges

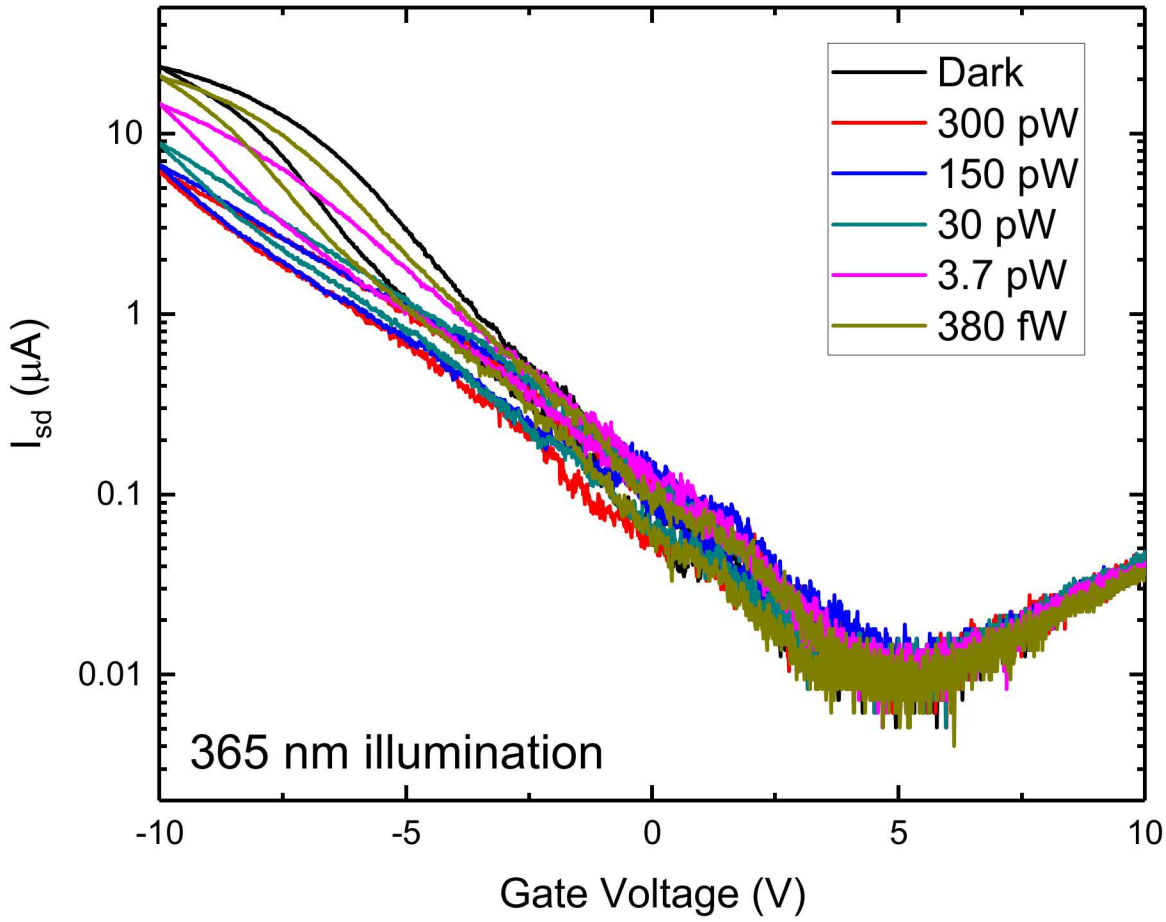


Positive charges from donors expected to give much higher response

Device Architecture Comparison



No Threshold Voltage Shift



High-Responsivity Time Constant