Quantum engineered nanowire room temperature IR detectors

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Principle of semiconductor photodetectors

\[ \hbar \omega \geq E_g \]
Infrared detection challenge at room temperature

- Semiconductor IR detectors need **small bandgap semiconductors** because IR photons have small energies ($\hbar \omega \geq E_g$).

- Phonons have energies comparable to those of IR photons and therefore can also excite electrons from the valence to the conduction band causing current in the dark.

- At room temperature, there are many more phonons than photons. Therefore, many more electron-hole pairs are generated by phonons than by photons. Large dark current and poor light-to-dark contrast ratio. Need cryogenic cooling.

$$CR = \frac{I_{\text{light}}}{I_{\text{dark}}} \approx 1$$
Project I: Solving the phonon catastrophe problem to enable room-temperature IR detection

Make electron-photon coupling much stronger than electron phonon coupling by employing wavefunction engineering

Rate at which electrons are excited from one energy level \((E_1)\) to another \((E_2)\) by either phonons or photons is given by Fermi's Golden Rule

\[
S(E_1, E_2) = \frac{(2\pi)^2}{\hbar} |M_{E_1, E_2}|^2 \delta(E_2 - E_1 - hf)
\]

\[
|M_{E_1, E_2}^\text{phonon}|^2 \propto N_{\text{phonon}} \left( \int_{-\infty}^{\infty} d^3r \psi_2^*(r) \psi_1(r) \right)^2
\]

\[
|M_{E_1, E_2}^\text{photon}|^2 \propto N_{\text{photon}} \left( \int_{-\infty}^{\infty} d^3r \psi_2^*(r) e_\nu \cdot \nabla \psi_1(r) \right)^2
\]

where \(e_\nu\) is the unit vector in the direction of light polarization

\(\therefore N_{\text{phonon}} \gg N_{\text{photon}}\): we have to make

\[
\left| \int_{-\infty}^{\infty} d^3r \psi_2^*(r) e_\nu \cdot \nabla \psi_1(r) \right|^2 \gg \left| \int_{-\infty}^{\infty} d^3r \psi_2^*(r) \psi_1(r) \right|^2
\]

in order to make the phonon and photon excitation rates at least comparable.
Project I: wavefunction engineering

\[
\left| \int_{-\infty}^{\infty} d^3r \psi_2^*(r) e \cdot \nabla \psi_1(r) \right|^2 \gg \left| \int_{-\infty}^{\infty} d^3r \psi_2^*(r) \psi_1(r) \right|^2
\]

Final state wavefunction

Initial state wavefunction

Conduction band

Valence band

Wavefunction in the conduction band

Wavefunction in the trap level

Fermi level

Filled trap level

10 nm

Wide-gap

Insulator

Substrate
Characterization

Nanowires electrodeposited in pores

Photoluminescence spectrum showing blue shift due to quantum confinement. Courtesy US Army ERDC.

EDS

IR absorption in nanowires
The final proof of photo-detection

Detection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detectivity</td>
<td>$1.18 \times 10^7$ Jones</td>
</tr>
<tr>
<td>Noise equivalent power</td>
<td>43.4 nW/$\sqrt{\text{Hz}}$</td>
</tr>
<tr>
<td>Responsivity</td>
<td>0.645 mA/W</td>
</tr>
<tr>
<td>Light-to-dark contrast ratio</td>
<td>2:1</td>
</tr>
<tr>
<td>Standby power dissipation</td>
<td>0.9 mW</td>
</tr>
<tr>
<td>Dark conductance</td>
<td>1 mS</td>
</tr>
</tbody>
</table>

From Physica E, 44, 1478 (2012)

(a) Trap to conduction band
(b) Valence to conduction band

Dual mode detectors

Trap to conduction band
Valence to conduction band
Gain: The antidote to poor quantum efficiency

- Many photons create one electron-hole pair if quantum efficiency is poor
- That pair must produce many more to generate appreciable photocurrent (i.e. it must exhibit “gain”).
- Usually one uses avalanching (impact ionization) which is very noisy
- We have a quieter process — photomodulated tunneling
The tunnel detector based on photomodulated tunneling

Saumil Bandyopadhyay, Pratik Agnihotri and Supriyo Bandyopadhyay.  
*Physica E, 44, 1478 (2012)*
Measured characteristic of the tunnel detector

Saumil Bandyopadhyay, Pratik Agnihotri and Supriyo Bandyopadhyay.

*Physica E, 44, 1478 (2012)*

US Patent 8,946,678
Capacitive photodetector: A potentially dissipation-less detector with infinite contrast ratio

\[ C = \frac{\Delta Q}{\Delta V} \]

Capacitive detector - $V_R$

Saumil Bandyopadhyay,

Spintronic photodetection

- No spin relaxation in spacer
- 100% spin injection/detection efficiency
- Carriers injected by one contact is completely blocked by other
- Dark current = 0

Almost no spin relaxation occurs in the spacer if only the lowest subband is occupied because of the complete suppression of D’yakonov-Perel’ relaxation.

\[
\text{Contrast ratio} = \frac{G_i}{G_d} = \frac{I_{\text{light}}}{I_{\text{dark}}} = \frac{1 - \xi_{\text{Co}} \xi_{\text{Fe}} + 2 \xi_{\text{Co}} \xi_{\text{Fe}} (L/L_i)}{1 - \xi_{\text{Co}} \xi_{\text{Fe}} + 2 \xi_{\text{Co}} \xi_{\text{Fe}} (L/L_d)} = \frac{L_d}{L_i} \text{ if } \xi_{\text{Co}} = \xi_{\text{Fe}} = 1
\]
Spintronic photodetection


Conclusions

1. Wavefunction engineered nanowire IR detectors produce relatively high detectivity at room temperature, but light-to-dark contrast ratio is still not large enough.

2. Tunneling photodetectors produce gain without avalanching and are "quiet".

3. Capacitive photodetectors are ideally capable of zero dark current and infinite detectivity but require an ac source.

4. Spintronic photodetector may lead to improved detection, but is still in its infancy.