optical properties of carbon nanotubes

Andreas Graw
motivation

Schematic sketch of a FET
(source: IBM)

Sketch of a display based on CNTs as emitter

Fluorescence of SWCNT
(source: Rice University)
outline

motivation

principles of carbon nanotubes

electronic properties

optical properties
  raman spectroscopy
  fluorescence

outlook
principles of carbon nanotubes

graphene unit cell
(a) in real space

(b) first Brillouin zone

principles of carbon nanotubes

Tight binding model
Only nearest neighbor interaction

\[
E(k_x, k_y) = \epsilon_{2p} + \gamma_0 \sqrt{1 + 4 \cos\left(\frac{\sqrt{3}a_0 k_y}{2}\right) \cos\left(\frac{a_0 k_x}{2}\right) + 4 \cos^2\left(\frac{a_0 k_x}{2}\right)}
\]

Source: M. Engel: Graphene and Carbon Nanotube based optoelectronic devices (2012)

with empirical parameters \( \epsilon_{2p} \) and \( \gamma_0 \)
principles of carbon nanotubes

**Electronic band structure**

Conduction and valence band touch at six distinct points at the Fermi energy $E_F$.

electronic properties

electronic band structure
quantization of allowed states along $\vec{k}_\perp$
and the continuity of states along $\vec{k}_\parallel$

principles of carbon nanotubes

optical properties

Raman spectroscopy
Inelastic scattering of monochromatic light due to interaction with molecular vibrations

\[ \Delta E_i = h\nu_0 \]
\[ \Delta E_e = -h\nu_0 \]
\[ \Delta E_i = h\nu_0 \]
\[ \Delta E_e = -h(\nu_0 - \nu_v) \]
\[ \Delta E_i = h\nu_0 \]
\[ \Delta E_e = -h(\nu_0 + \nu_v) \]

Rayleigh scattering
Stokes scattering
anti-Stokes scattering
optical properties

Raman spectroscopy
 stronger Raman signal for resonance with van Hoven singularities

→ information about DOS of CNTs

optical properties

Raman RBM

\[ D(\text{nm}) = \frac{248}{\omega_{\text{RBM}}} \]


density of states for a 1D system

\[ D(E) = \sqrt{2m^*} \frac{1}{\pi \hbar^2 L_x L_y L_z} \sum \frac{1}{\sqrt{E - E_k}} \]

For \( E - E_k = 0 \): \( D(E) \to \infty \)

Optical transitions \( \leftrightarrow \) electron-electric dipole transitions

\[ \Delta E = \pm 1 \]
\[ \Delta m = \pm 1, 0 \]
optical properties

optical transitions

<table>
<thead>
<tr>
<th>$\lambda_{11} (nm)$</th>
<th>$E_{11} (eV)$</th>
<th>Helicity $(n,m)$</th>
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<tr>
<td>952</td>
<td>1.302</td>
<td>(8,3)</td>
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<tr>
<td>1023</td>
<td>1.212</td>
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</table>

optical properties

extinction of bundled SWNT

optical properties

fluorescence

red shift of fluorescence of approximately 45/cm from absorption spectrum

optical properties

single SW-CNT spectroscopy

optical properties

single SW-CNT spectroscopy

optical properties

length dependence of fluorescence

(10,2) SWCNTs

NIR Image

Total Intensity

optical properties

coulomb interactions - excitons
discrepancy with tight binding model

optical properties

two photon excitation
direct measurement of excitons → binding energy of ~400meV

outlook

90 companies with an annual budget ~100 Mio. €

projects:
- electronics
- lightweight constructions
- energy
...

Source: http://www.cnt-initiative.de
Source: http://www.soci.org
Source: http://www.physorg.com
references

Thank you for your attention!