What is Nanophysics: Survey of Course Topics

Branislav K. Nikolić
Department of Physics & Astronomy, University of Delaware, Newark, DE 19716, U.S.A.

https://wiki.physics.udel.edu/qttg
Definition of Nanophysical Systems

**Definition:** Any condensed matter systems whose at least one (out of three) dimension is of the order of nanometer can be considered as nanoscale system.

Nanoscience and nanotechnology are all about relating and exploiting phenomena for materials having one, two or three dimensions reduced to the nanoscale. Their evolution may be traced to three exciting happenings that took place in a short span from the early to mid-1980s with the award of Nobel prizes to each of them. These were: (i) the discovery quantum Hall effect in a two-dimensional electron gas; (ii) the invention of scanning tunnelling microscopy (STM); and (iii) the discovery of fullerene as the new form of carbon. The latter two, within a few years, further led to the remarkable invention of the atomic force microscope (AFM) and, in the early 1990s the extraordinary discovery of carbon nanotubes (CNT), which soon provided the launch pad for the present-day nanotechnology. The STM and AFM have emerged as the most powerful tools to examine, control and manipulate matter at the atomic, molecular and macromolecular scales and these functionalities constitute the mainstay of nanotechnology. Interestingly, this exciting possibility of nanolevel tailoring of materials was envisioned way back in 1959 by Richard Feynman in his lecture, “There’s plenty of room at the bottom.”
What is nanophysics?

W. Pauli: “God made solids, but surfaces were the work of Devil.”

\[
\Psi(\mathbf{r}) = e^{i\mathbf{k} \cdot \mathbf{r}} u_k(\mathbf{r}) \rightarrow \Psi_{\text{surf}}(\mathbf{r}) = e^{i\mathbf{k}_\parallel \cdot \mathbf{r}_\parallel} u_{k_\parallel}(\mathbf{r}_\parallel) e^{-\mathbf{k}_\perp \cdot \mathbf{r}_\perp}
\]
Two-Dimensional Materials Beyond Graphene and van der Waals Heterostructures

A van der Waals heterostructure is a type of metamaterial that consists of vertically stacked two-dimensional building blocks held together by the van der Waals forces between the layers.

MoS$_2$

Graphene
Branches of Nanophysics and Nanotechnology

Quantum Transport

Introduction to Nanoelectronics

Principles of Nano-Optics

Carbon Nanotubes

Magnetic Nanoparticles

Nanomagnetism and Spintronics

Nanofluidics: Nanoscience and Nanotechnology

Nanoplasmonics: The physics behind the applications
Experimental Tools of Nanophysics: STM and AFM

The main function of the feedback system is to move the sample and the tip relative to each other. The movement in the plane of the sample is called raster-scanning, and is well-defined once the user sets the scan area and scan speed (Figure 4a). The movement out of the plane of the sample is completely unpredictable, and it is this movement that underlies the construction of three dimensional topography images. The height of features in an AFM image is determined by how far up and down the tip or sample move relative to each other in order to maintain a constant tip-sample interaction force. In some AFMs the tip moves up-down while the sample stays at a constant height; in other AFM’s this scheme is reversed. The end result is, in principle, the same.
Examples of STM Images

Fe on Cu(111)

IBM Almaden

Origin of spatial charge inhomogeneity in graphene
Yuanbo Zhang1,*, Victor W. Brar1,2,*, Caglar Giril1,2, Alex Zettl1,2 and Michael F. Crommie1,2

(a)

(b)
Physical Meaning of Dirac Materials and Topological Protection Revealed by STM

perturbing topologically trivial Dirac material such as graphene

perturbing topological insulators as Dirac materials with nontrivial topology of wave functions in the bulk

Bi$_2$Se$_3$ surface + impurity: SSC 152, 747 (2012)
Examples of AFM Images

**Science 319, 1229 (2008):**
Graphene Nanoribbons with ultrasmooth edges

**Kouwenhoven Lab:**
Double quantum dot integrated with quantum point contacts on both sides as a spin-based qubit
Why are Nanostructures Interesting for Basic Research on Weakly Interacting Electrons?

- Enhanced role of surface atoms with unpaired spins and uncompensated bonds
- Reduced dimensionality at the nanoscale = strongly modified density of states, enhanced Coulomb interaction, ...
- Quantum confinement effects = discrete energy levels
- Quantum interference effects in transport = quantum transport

Semiclassical vs. Quantum Transport

\[ P_{cl} = P_1 + P_2 \text{ vs. } P_{qm} = |A_1 + A_2|^2 \]

\[ P_{qm} = P_1 + P_2 + 2\sqrt{P_1P_2}\cos\phi \]
Example: Conductance Quantization

PRL 60, 848 (1988)

PRB 78, 161409(R) (2008)
Classical and Quantum Hall Trio

**Classical**

- **Ordinary Hall effect**
  - with magnetic field $H$
  - Hall voltage but no spin accumulation

- **(Pure) spin Hall effect**
  - no magnetic field necessary
  - No Hall voltage but spin accumulation

- **Anomalous Hall effect**
  - with magnetization $M$
  - (carrier spin polarization)
  - Hall voltage and spin accumulation

**Quantum**

- Quantum Hall
- Quantum spin Hall
- Quantum anomalous Hall

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**What is nanophysics?**
Example: Resistance Quantization in Quantum Hall Effect

Theoretical explanation introduces topologically protected edge states which play a key role in all recently discovered topological materials.
Example: Nonlocal Resistance in Multiterminal Graphene-Based van der Waals Heterostructures

- Direct and inverse spin Hall effect
- Direct and inverse valley Hall effect

**Theory:**
- PRL 117, 176602 (2016)
- PRB 93, 155104 (2016)
- Nat. Commun. 5, 4875 (2014)

**Science** 346, 448 (2014)

Example: Good and Bad Quantum Tunneling

Good

Nobel Prize in Physics 1973

Negative differential resistance region

Voltage (V) →

Good

Tunnel magnetoresistance

Good

Gate

Gate Oxide

N+ Pocket

P+ Source

N Drain

Buried Oxide

Good

Gate

Gate Oxide

N+ Pocket

P+ Source

BTBT

Buried Oxide

Bad

Source

Drain

Lg=4 nm

Spectral Current

Log Scale Drain Current (I_d)

Gate Voltage (V_G)

GATE

GATE SOURCEREGION

Threshold region

Source

Drain

4 nm

7 nm

10 nm

13 nm

What is nanophysics?
Example: Quantum Pumping of Charge and Spin

Science 283, 1905 (1999)

An Adiabatic Quantum Electron Pump

M. Switkes, C. M. Marcus, K. Campman, A. C. Gossard


Ni_{81}Fe_{19}

Pt

\[ \sigma \rightarrow J_s \]

\[ E_{ISHE} \]

Ni_{81}Fe_{19}

Pt

\[ \sigma \rightarrow J_s \]

\[ E_{ISHE} \]

PRB 79, 054424 (2009)

arXiv:1803.04404
Why are Nanostructures Interesting for Basic Research on Strongly Interacting Electrons?

**LETTER**

Controlling many-body states by the electric-field effect in a two-dimensional material

- **ARTICLE**

Unconventional superconductivity in magic-angle graphene superlattices

- **LETTER**

Correlated insulator behaviour at half-filling in magic-angle graphene superlattices

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**PHYS824: Nanophysics & Nanotechnology**

What is nanophysics?
Limits of Top-Down Approach in Conventional Electronics

(x,y,θ) alignment of mask to substrate
uniform UV exposure illumination
latent image created in photoresist after exposure
wet chemical development

NEGATIVE PHOTORESIST
Photosensitive polymeric material is exposed and rendered insoluble to the developer solution.

POSITIVE PHOTORESIST
Exposure decomposes a development inhibitor and developer solution only dissolves photoresist in the exposed areas.

PHYS824: Nanophysics & Nanotechnology

What is nanophysics?
Fundamental Quantum Effects at Nanoscale Act Against Moore’s Law for Conventional FETs

Nonscaling effects at nanometer MOSFETs:

- quantum tunneling of carriers through the gate insulator and through the body-to-drain junction
- dependence of sub-threshold behavior on temperature
- discrete doping effects
- power dissipated in various leakage mechanisms

PRL 98, 026802 (2007)
Nanotechnology:
Nanoelectronics with GNRs and CNTs

What is nanophysics?
Nanotechnology:
Spintronics and Optospintronics

What is nanophysics?
Nanotechnology: Nanoscale Thermoelectrics

\[ ZT = \frac{S^2GT}{\kappa_{\text{el}} + \kappa_{\text{ph}}} \]

Nanoscale Thermoelectrics

Nano Lett. 14, 3779 (2014)
Nanotechnology: Nano-Bio Interface

Graphene nanodevices for DNA sequencing
Stephanie J. Heerema and Cees Dekker*

Nano Lett. 12, 50 (2012)

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