What is Nanophysics: Survey of Course Topics

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**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.”

**Nobel Prize in Physics 2007**
W. Pauli: “God made solids, but surfaces were the work of Devil.”

\[ \Psi(\mathbf{r}) = e^{i\mathbf{k} \cdot \mathbf{r}} \psi_k(\mathbf{r}) \rightarrow \Psi_{\text{surf}}(\mathbf{r}) = e^{i\mathbf{k}_{||} \cdot \mathbf{r}_{||}} \psi_{k_{||}}(\mathbf{r}_{||})e^{-\mathbf{k}_{\perp} \cdot \mathbf{r}_{\perp}} \]
Branches of Nanoscience

- Quantum Transport
- Introduction to Nanoelectronics
- Principles of Nano-Optics
- Nanomagnetism and Spintronics
- Carbon Nanotubes
- Magnetic Nanoparticles
- Nanoparticles

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What is Nanophysics?
Why are Nanostructures Interesting for Basic Research?

- Enhanced role of surface atoms with their 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 coherent effects in transport = quantum transport

Semiclassical vs. Quantum Transport of (quasi)Electrons

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

\[ P_{\text{qm}} = P_1 + P_2 + 2\sqrt{P_1P_2} \cos \phi \]
Limits of Top-Down Fabrication in Applied Physics and Electrical Engineering

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Fundamental Quantum Effects Acting Against Moore’s Law

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)
Nanostructures: Bottom-Up Approach

Fuhrer Lab, College Park
Avouris Lab, IBM

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Nanostructures Explored in PHYS824

THE MOTHER OF ALL GRAPHITES

Graphite (below top), a pile of carbon atoms that resembles chicken wire, is the basic building block of all the “graphitic” materials depicted below. Graphite (bottom row at left) is the main component of pencil “lead,” a crumbling substance that resembles a layer cake of weakly bonded graphene sheets. When graphene is wrapped into rolled forms, fullerenes result. They include honeycombed cylinders known as carbon nanotubes (bottom row at center) and soccer ball-shaped molecules called buckyballs (bottom row at right), as well as various shapes that combine the two forms.
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 AFM's 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.
**STM Images**

**Fe on Cu(111)**

**IBM, Almaden**

**What is Nanophysics?**

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**FIG. 1.** (Color online) (a) Schematic of a mechanically exfoliated monolayer graphene flake (gray) with gold electrodes on a SiO₂ substrate. (b) STM topographic image of monolayer graphene showing the hexagonal lattice as well as the underlying surface corrugations. The scale bar is 2 nm. The imaging parameters are sample voltage $V_s=0.25$ V and tunneling current $I_t=100$ pA.

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**FIG. 2.** (Color online) $dI/dV$ point spectroscopy shows a linear relationship between the tunneling conductance and the sample voltage $V_s$. The inset shows the region near the Fermi level; no gap is seen.

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**FIG. 3.** (Color online) (a) STM topography showing the lattice and surface corrugations. The scale bar is 8 nm. The topography is recorded with $V_s=0.4$ V and $I_t=100$ pA. (b–(f)) $dI/dV$ maps at sample voltages −0.2, 0.0, 0.2, and 0.4 V, respectively, showing electron and hole puddles. For all the images, the current was stabilized at the parameters of (a) and the feedback was then switched off. The maps were recorded using lock-in detection. (f) Spatially averaged $dI/dV$ curves at five different regions of the graphene indicated in (a). The curves show a crossover near 0.2 V as a result of the shifting Dirac point.
Dai Lab, Science 319, 1229 (2008): Graphene Nanoribbons with ultrasmooth edges

Kouwenhoven Lab: Double quantum dot integrated with quantum point contacts on both sides for spin qubit experiments
Equilibrium Nanophysics: Electronic Structure and Density of States

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Nonequilibrium Nanophysics: Quantum Transport

Externally set energy scales:

\[ k_B T, eV_{bias} \]

\[ G_Q = \frac{e^2}{\pi \hbar} \]

Internal energy scales:

\[
\delta_s, E_C, E_{Th} = \frac{\hbar}{\tau_{esc}} \simeq \delta_s \frac{G}{G_Q}, E_{in} = \frac{\hbar}{\tau_{in}}
\]
Conductance Quantization

van Wees et al., PRL 60, 848 (1988)

Avouris Lab, PRB 78, 161409(R) (2008)
Imaging Electron Flow

New scanning probe techniques provide fascinating glimpses into the detailed behavior of semiconductor devices in the quantum regime.

Mark A. Topinka, Robert M. Westervelt, and Eric J. Heller

December 2003  Physics Today  47
Quantum Hall Effect in 2DEG and Graphene

Magnetic field

Quantum Hall system
Quantum spin Hall system

Theory

Voltage Probe
Hall Bar
Landau Level
Edge State

What is Nanophysics?
Weak Localization

Any interference effects present in diffusive conductors?

We have to look at the pairs of trajectories!

\[ |A|^2 = |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2 |A_1 A_2| \cos \theta \]

Averaging: destroys interference effects? Not exactly!

Still looking for interference effects.

\[ A_1 = A_2 \]

Take special pairs of trajectories!

Electron has to pass the same point twice: Conductance is suppressed by interference.

\[ |A|^2 = |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2 |A_1 A_2| = 4 |A_1|^2 \]

Interference effects double the classical contribution and (slightly) suppress the conductance.

Let us switch on the magnetic field:

\[ A_1 \rightarrow A_1 e^{i\phi}, A_2 \rightarrow A_2 e^{-i\phi} \]

\[ \phi = 2 \pi \Phi / \Phi_0 \]

\[ |A|^2 = |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2 |A_1 A_2| \cos 2\phi \]

Average over different loops: Interference term disappears! Magnetic field destroys weak localization!!!

This is why it is observable!
Strong (Anderson) Localization

Extended wavefunction

Localized wavefunction

Direction of propagation

Localized states

Extended states

$\delta = 2.4$

$\delta = 2.0$

$\delta = 1.6$

$\delta = 1.2$

$\delta = 0.8$

$\delta = 0.4$

$R$

$\alpha T$

$\frac{T}{\theta_d}$

$\alpha T^5$

0.1

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What is Nanophysics?
Electronic Interferometers and Quantum Nonlocality

Fig. 8.2 AB effect as observed in a gold ring (the sample is shown in the inset). In (b) the Fourier spectrum of the raw data in (a) is shown. A strong $eS/h$ frequency is observed, while the second order $2eS/h$ is much weaker. After [316].
Quantum Tunneling

Giant magnetoresistance

Tunnel magnetoresistance

(a) spin dependent scattering

(b) spin dependent tunneling
Coulomb Blockade

FIG. 1  (a) Schematic illustration of a confined region (dot) which is weakly coupled by tunnel barriers to two leads. (b) Because the charge $Q = -N e$ on the dot can only change by multiples of the elementary charge $e$, a charge imbalance $Q + C \phi_{\text{ext}}$ arises between the dot and the leads. This charge imbalance oscillates in a saw-tooth pattern as the electrostatic potential $\phi_{\text{ext}}$ is varied ($\phi_{\text{ext}}$ is proportional to the gate voltage). (c) Tunneling is possible only near the charge-degeneracy points of the saw-tooth, so that the conductance $G$ exhibits oscillations. These are the “Coulomb-blockade oscillations”.

H. van Houten, C. W. J. Beenakker, and A. M. Staring, cond-mat/0508454

Ensslin Lab, APL 92, 012102 (2008)
Nanophysics Applications: Spintronics (GMR, TMR, Spin-Torque)

What is Nanophysics?
Nanophysics Applications: Nanoelectronics with GNRs and CNTs

What is Nanophysics?