Questions to Introduction and Chapter 5 of TH

1. What is Moore’s law? Why do we need Nanophysics?

2. What happens to the laws of physics on a mesoscopic scale? Give an example.

3. What are characteristic length scales and specific parameters that define transition to mesoscopic regime?

4. What is de Broglie wavelength of electrons and size quantization?

5. What length scale is important for a double slit experiment in the solid state? Please explain.

6. What is the role of charging effects on nano-scale?

7. What length scale is important for ballistic transport? How is it influenced by temperature?

8. Does a ballistic wire have infinite conductance?

9. What is the quantum of conductance? Where does it appear? What is the value of quantum resistance in Ohm?

10. What is the quantum point contact (QPC), and at what temperatures and lengths does it usually operate? What length scale is important for QPC?

11. What is the quantum Hall effect and Shubnikov–de Haas oscillations? Are these effects linked? In what systems do they take place? In what units is resistance quantized? What temperatures and magnetic fields are essential for these effects?

12. What is the role of Fermi wavelength in changing the dimensionality of mesoscopic systems? Is it related to de Broglie wavelength? What are the implications of changing dimensionality? What is the density of states as function of energy per unit volume in systems of different dimensions? Can you derive this?

13. What is the Aharonov–Bohm effect? What is its typical geometry? What length scale is important for this effect, and by what kind of scattering is it influenced? Is resistance a local property in this effect? Is high magnetic field and low temperatures necessary for it?

14. What is single-electron tunneling and the role of capacitance in this effect? What is the characteristic energy that plays a major role in this effect?

15. What is a quantum dot and what is its relation to single electron quantum transistor?

16. What is the role of electron spin in solid-state physics? What characteristic length scale is important in nano-spintronics? Do you know any commercial devices that use spin of electrons?

17. What energies and temperatures are typical for mesoscopic electronic devices? What is the relation between temperature and electron energy? What is typical length scale at which the mesoscopic regime takes place at different temperatures?

18. What semiconducting materials are usually used in the nano-industry and nanophysics experiments? What are reasons for that?

19. What applications of nanophysics do you know?

20. What determines the temperature at which a mesoscopic effect vanishes? How is it in contrast with superconductivity?

21. Why does Fermi wavelength decrease with the electron density? What is the relation between Fermi wavelength and electron density in different dimensions? Can you derive this? Can you find mistakes in TH p. 158 (pdf)?

22. What is quantum scattering length and quantum scattering time? Is it the same as Drude scattering time τ?

23. How does dephasing time of electrons depend on T at low and high temperatures?

Questions to Chapter 2 TH: 'An Update of Solid State Physics'

1. What is Bravais lattice? Give an example.

2. What are primitive and composite lattices? How many fundamental lattices exist in 1, 2 and 3 dimensions? Name and draw a few.

3. What is the Wigner-Zeitz cell? How is it built?

4. What is the Reciprocal Lattice? What is it used for? What are the basic vectors of the reciprocal lattice? What is its first Brillouin zone?

5. Describe crystal structures of GaAs, Si, Ge, CdSe and ZnS, which are important materials for Nanophysics. What are their first Brillouin zones?

6. Is crystal lattice of nano materials different from crystal lattice of bulk materials?

7. What are Bloch wave functions? What main feature of Solid State do they reflect?

8. What is the reason for the appearance of energy bands? Describe ***nearly free electron*** and ***tight binding*** models.

9. What is transfer integral and overlap integral in the **tight binding model**? What is energy dispersion? Is it coming from the requirement that the wave functions have to obey the Bloch theorem?

10. What is the difference between metals, semiconductors and insulators? Draw their band structures. Are semiconductors just small-bandgap insulators? What gap value (in electron Volts) is considered to be large enough for an insulator? Is semiconductor with zero bandgap possible?

11. Discuss valence and conduction bands in Ga–As and Si. What are their typical effective masses of charge carriers?

12. What is indirect bandgap? Why is Si a poor material for optoelectronics?

13. Does bandgap change with temperature and doping? Give an example. (The bandgap increases with decreasing temperature and increasing doping ($Al_xGa_{1-x}As$).)

14. What are electron density, density of electronic states and occupation probability? How they are linked?

15. What is the energy dependence of the density of electronic states in 0, 1, 2 and 3 dimensions? Can you derive this?

16. What is the equilibrium occupation probability for fermions? Does it have anything to do with the Fermi–Dirac distribution function? What is chemical potential? At what condition is chemical potential equal to Fermi energy?

17. What is intrinsic carrier concentration in semiconductors? How does it depend on temperature in the limit $|E_{C,V} - \mu| >> k_B\Theta$?

18. What are effective densities of state for intrinsic carriers and law of mass action for charge carriers?

19. How does chemical potential depend on temperature and mass of intrinsic charge carriers in the limit $|E_{C,V} - \mu| >> k_B\Theta$?

20. What are envelope wave functions? Why are they needed and how are they built? Does the envelope wave equation contain (periodic) crystal potential and perturbation potential? Is energy of the bottom (top) of the band there?

21. Why is doping necessary? Consider a Si atom replacing a Ga atom in a GaAs crystal. Can we use envelope wave equations for the electron to describe doped states? What is the trajectory and radius of a doped electron?

22. What are donors and acceptors, neutral and ionised dopants? What is the charge neutrality formula?

23. In what way electron density of a doped semiconductor and the chemical potential depend on temperature? Name three main regimes.

24. What is diffusive transport? How is it related to Boltzmann's equation and displacement of Fermi sphere? What is mobility of charge carriers? How does diffusive transport result in Ohm's law and Drude's formula?

25. What is drift velocity? Describe the motion of electrons in electrical and magnetic fields.

26. What is conductivity and resistivity tensor?

27. How to find longitudinal and transverse voltage of a semiconductor sample? What is Hall coefficient and how is it linked with charge carriers' density?

28. What is diffusion current and relation between diffusion coefficient and mobility of charge carriers in 1, 2 and 3 dimensions (Einstein relations)?

29. What are main scattering mechanisms in semiconductors and their influence on mobility of charge carriers and its temperature dependence?

Questions to Chapter 3 TH: 'Surfaces, Interfaces, and Layered Devices'

1. Why are surfaces important in Nanophysics? Are their properties different from bulk?

2. What are *work function* and *electron affinity*? Why does the latter need to be introduced in semiconductors and insulators?

3. What is the origin of surface states? Where do they come from and where are they located in band structures of semiconductors?

4. What is the origin of band bending? At what conditions and in what materials does it happen? Is charge redistribution important for this process?

5. How do surface states appear in the tight binding model in crystal-vacuum interface? Have they got anything to do with Bloch's theorem solutions with imaginary wave vectors and evanescent waves? Give an example of a surface wave function in one dimension.

6. Is it possible to have contribution to surface states from different bands? Can they be of different character of doping (n, p)?

7. Can surface states be derived from the nearly-free-electron model? Does the imaginary part of the wave vector play a role there? Does the model of nearly free

electrons give qualitatively different results from the tight binding model?

8. Can different types (donor-like and acceptor-like) of surface bands be partially filled? What is the 'charge neutrality level' in semiconductors with intrinsic charge carriers? To what energy level are surface states filled in a neutral and a charged surface?

9. What is surface depletion layer in n-doped semiconductors? How thick is it typically? What is the link between surface and bulk density of states in doped semiconductors?

10. What is a typical ratio of surface charge density to integrated density of surface states? Does chemical potential at the surface change a lot due to the charge transfer? What is Fermi level pinning by the surface states?

11. What are *induced gap states* (ISG) close to a metal-semiconductor interface? Are IGSs semiconductor-specific? What are they built from?

12. What is the consequence of a charge moving from metal to semiconductor? What is the extent of the formed dipole? What is the Schottky barrier? Does redistribution of dopants in bulk change this picture? What is the scale of dopants redistribution in space?

13. How does the Schottky barrier height depend on *work function* of different metals in contact with the

semiconductor? How is the Schottky barrier height calculated? What is its typical value in eV?

14. What is a Schottky diode and how does it work?

15. Describe how to make Ohmic contact to a semiconductor.

16. What are heterointerfaces? Explain 2 different scales of charge redistribution in p-n heterojunctions. Do induced gap states appear there? What are 3 basic types of band alignments in semiconductor heterointerfaces? What are staggered and misaligned alignments?

17. What are MOSFET and HEMT? Which device is based on Si and which on GaAs? Illustrate MOSFET by drawing. How does it differ from a Schottky diode? Does this transistor rely on the electrostatic field effect?

18. What is inversion and accumulation in MOSFET? What are ambipolar devices?

19. What are specific properties of the electron gas that is formed at the O–S interface in MOSFET (density, spatial extent, possibility of energy quantisation, separation from the ionised donors, impurity scattering, mobility, effective mass, location with respect to interface)? What is two-dimensional electron gas (2DEG)? What is quasi-two-dimensional electron gas?

20. Where are Si MOSFET circuits used? What are advantages of Si MOS material systems? What is complementary MOS (CMOS) concept? How can CMOS circuits reduce power

consumption? What are NOT and NAND gates? How could NAND gates be used for building a storage cell?

21. What is the design of Ga[Al]As high electron mobility transistor (HEMT)? What is the principle of modulation doping? What determines the density of the 2DEG in HEMT? How can it be tuned?

22. What allows increasing electron mobility and mean free path in HEMT and what is the progress over years? Do these parameters depend on temperature?

23. What is a parabolic quantum well and how can it be made?

24. What semiconductors can be combined in layered devices? What is the bandgap engineer's map? Give an example of an efficient quantum well system. Are organic FETs possible?

25. Are properties of quantum confined carriers different from those in the bulk? Can effective masses of holes be reversed in quantum wells? Is screening different in quantum wells from that in 3D systems?

26. What are main scattering mechanisms in HEMT? What is the difference between scattering in quantum well systems and 3D materials? Is further progress in increasing electron mobilities in quantum-well systems expected? Is inter-band scattering important?

Questions to Chapter 4 TH: ‘Experimental Techniques’

1. What are main single crystal growth techniques in the semiconductor industry? What material are they used for? Please describe the techniques.

2. How are clean rooms classified? What is a class 100 clean room?

3. What are main techniques in growth of layered semiconducting materials? Please describe them.

4. What are advantages and disadvantages of MOCVD in comparison with MBE?

5. Describe the principle of RHEED control in MBE.

6. What is cleaved edge overgrowth (CEO) technique? Please describe it. What kind of nanostructures can be grown by it?

7. What are self-assembled quantum dots? How can they be grown? Describe the role of surface energy in their appearance. Analyse energy conditions for three different types of film growth: continuous layer, islands and islands with wetting layer growth.

8. Explain SAQD superlattice growth. What is the role of stress created by the first layer of quantum dots in the appearance of the following dots above? How can stress be expressed in surface energy equations?

9. What is atomic force microscopy? Explain how it works. What is its relation to scanning probe microscopy?

10. What is optical and electron beam lithography? Explain techniques of metal etching, lift-off and substrate etching? Why does one need all these different techniques for patterning semiconductors?

11. What is positive and negative photoresist? Please explain how photoresists work. Is it works different for optical and electron beam lithography?

12. Give examples of direct writing methods in nano-lithography. What advantages and disadvantages they have compared with traditional lithography?

13. What are main techniques of etching used in semiconductor industry and research?

14. Describe procedures of metallization. What is *angle evaporation*? Explain its advantage in comparison with other techniques.

15. How to prepare Ohmic contacts to layered nano-structures? What materials and techniques are usually used? Is Schottky barrier an obstacle? Is position of contacts important for high field applications?

16. What are main techniques of attaching wires to the Ohmic contacts and to the gate electrodes? Explain how wedge bonding works.

17. Why are low temperatures needed in nanophysics? Why is liquid helium used as main cryogenic liquid? Why does not helium solidify when temperature is lowered?

18. What is superfluid helium? At what temperature does helium become superfluid? What are its properties?

19. What are the main properties of ^{3}He? How are they different from the properties of ^{4}He and why?

20. What is the specific property of ^{3}He/^{4}He mixture that can be used in dilution refrigerator? Describe phase separation.

21. What are the main types of ^{4}He cryostats? Please describe them. Is there any advantage of substituting ^{4}He with ^{3}He?

22. What is the principle of work of the ^{3}He/^{4}He dilution refrigerator? Please describe it in detail.

Questions to Chapter 6 TH: 'Magneto-transport Properties of Quantum Films'

1. Why are transport experiments in external magnetic fields needed in nanophysics? What parameters can be tuned in these experiments and what values can be determined from them? What means the condition $\omega_c \tau \geqslant 1$.

2. Describe the solution of the Schrödinger equation for two-dimensional electron gas in perpendicular magnetic field in the Landau gauge **A** = (−By, 0, 0) for a rectangular

sample of an area $L_x \times L_y$. Introduce cyclotron frequency. Where are harmonic oscillators centred? What are the eigenfunctions of the x–y Hamiltonian and the corresponding energy eigenvalues? What are wave functions in rotationally-invariant gauge?

3. What are Landau levels and magnetic length? Calculate the density of states of an ideal 2DEG in a perpendicular magnetic field.

4. Explain the meaning of filling factor ν for Landau levels. What $\nu = 2j$ means? When is the spin degeneracy lifted in the sufficiently strong magnetic field, what an odd integer value of ν corresponds to?

5. What is the way to vary the occupation of Landau levels? What is the integrated density of states D_{LL} in each Landau level? In what state is the system when electron density is equal to j D_{LL}, where j is integer? At what magnetic fields appear these states? Are these states extended in Fermi Energy – electron density and magnetic field diagrams in an ideal system?

6. Can insulating behaviour in 2DEG be extended over non-zero intervals of magnetic field? If yes, what could be the reason of this extension?

7. What spectroscopic technique could be used to measure the density of states in 2DEG and its evolution in magnetic fields? How chemical and electrostatic potentials contribute to the voltage in the technique? What is the rule for combining geometric capacitance and a ‘chemical capacitance’ into the effective

capacitance? Can density of states be extracted from capacitance spectroscopy experiments if the geometrical capacitance is known?

8. Describe main features of the quantum Hall effect (QHE). In what units is resistance quantised? How accurate is quantization in Hall plateaus? What is the resistance in the first plateau? What is the fractional QHE and what are the reasons for its appearance?

9. What are Shubnikov–de Haas oscillations? How are they linked with quantum Hall effect? What is the accuracy of longitudinal resistivity being equal to zero in the regions of quantized Hall resistance? Explain how Hall conductance and Hall resistance on plateau can be simultaneously equal to zero. Compare conductivity tensor in classical and quantum case.

10. What is the role of disorder in quantum Hall effect? How the states in the wings of the peaks of density of states can be localized? Do you know alternative explanations of quantum Hall effect?

11. Does quantum Hall effect exist in 3D systems? What is the density of state for free electron gas in strong magnetic field? How is this density of states modified in periodic superlattices confining electron motion in the direction along the magnetic field?

12. Explain the nature of Shubnikov–de Haas oscillations. How is it possible to use them to determine the quantum scattering time and effective mass of charge carriers?

13. How are Shubnikov–de Haas oscillations modified in the presence of two energy subbands? What could be used oscillations in this case for? What is the reason of parabolic background in the magnetic field dependence of longitudinal resistance?

14. How to map relative wave function probability density in different subbands using Shubnikov–de Haas oscillations in a parabolic quantum well with δ-function doping?

15. Explain the reason of the displacement of the quantum Hall plateaux in 2DEG with anisotropic potential profile. What is the effect of repulsive and attractive scatterers?

16. What is the influence of parallel magnetic field on 2DEG? What parameters can parallel field tune? What can it be used for? Give an example of typical experiment with parallel magnetic field.

Questions to Graphene

1. Describe graphene and its crystal lattice. What is its difference from other forms of carbon? What kind of hybridisation is realised in graphene? Describe other types of carbon hybridisation; give examples of compounds where it takes place.

2. Does graphene show quantum Hall effect (QHE)? Is it usual quantum Hall effect? If not, what is the difference? Is graphene a 2DEG? What is its density of states as

function of energy? Is any difference in QHE for the single layer and double-layer graphene?

3. Describe reciprocal lattice of graphene. How are inequivalent points in honeycomb lattice reflected in the structure of the first Brillouin zone?

4. What is the area of unit-cell in graphene. What are the σ and π bonds? How to calculate density of valence electrons in graphene? What is its value?

5. What are main techniques of graphene fabrication? Is exfoliated graphene different from epitaxial graphene? What substrates are used to visualise graphene optically? What are the definite techniques for identifying graphene?

6. Formulate Tight-Binding Model for electrons in graphene. What is the complication in graphene in comparison with Tight-Binding Model for simple honeycomb lattice? Introduce the energy overlap integral.

7. Describe energy dispersion of π electrons in graphene. How can it be obtained in Tight-Binding Model?

8. What is energy dispersion in graphene close to conic (Dirac) points? How is energy linked with wave vector there? Is Fermi velocity included in the link between energy and wave vector? What is trigonal warping?

9. What technique do you know that is suitable to map the energy dispersion of electrons? What is result of its application to graphene?

10. What is the rest mass of charge carriers in graphene? How to introduce its cyclotron effective mass? Does it depend on charge carriers density and how?

11. Is it possible in tunnelling that transmission becomes better when the barrier height increases? Does it anything to do with graphene? What is the Klein tunneling? How can electron go from conduction to valence band without backscattering?

12. Describe anisotropic and resonant scattering in graphene. What is the property of a barrier at angles close to the normal incidence? Describe the experimental realization of *n-p-n* junction in graphene.

13. What happens with the conductance of graphene when its Fermi level reaches the conic point? Does it go to zero? If not, at what value it stops?

14. What is specific about the level quantization and quantum Hall Effect in graphene? Are Landau levels equidistant? What is the number of states per Landau level? Does it linked with the number of magnetic flux quanta through the cell?

15. How to tune density of electrons in graphene? What is graphene's typical mobility of electrons? How is it dependent on temperature? What is the mean free path of electrons at room temperature? Can one see quantum Hall effect at room temperature?

16. What applications of graphene do you know? What is their importance?

Questions to Chapter 7 'Quantum Wires and Quantum Point Contacts'

1. What is quantum of resistance in magnetic and transport measurements of nanostructures? Are these quanta different and if yes – why? Give examples of quasi one-dimensional nanostructures. What characteristic length scales are most important in nanophysics of Quantum Wires and Quantum Point Contacts, and how to classify them? Is effective mass approximation suitable to describe quantum wires? What is the exception from this rule?

2. What are diffusive and ballistic quantum wires? What kind of wires is described by the formalism of R. Landauer and M. Büttiker? Can you describe main features of this formalism?

3. What is parabolic quantum well wire and how to define its density of states? How reflects the density of states one-dimensional character of the wire? Describe parabolic confinement model.

4. Describe magnetic field effect in parabolic-confinement model. What is characteristic cyclotron frequency in this case and how is it related to characteristic frequency of 2DEG? How is effective mass renormalized in this case? Are oscillations of the density of states periodic in 1/B?

What happens in very strong and very weak magnetic fields?

5. What is dependence of the resistance of quantum wire on magnetic field? Does magnetic field influence density of state in the wire? Are minima of resistance periodic in 1/B? How can the position of resistance minima be used to find electronic wire width?

6. What is 'wire peak' and how boundary scattering influences resistance of quantum wire? At what cyclotron radius is the fraction of electron trajectories close to the wire edge maximised? Describe behaviour of the system with rough edges.

7. Can conductance of quantum wires and point contacts be quantised in the absence of magnetic field and if yes, in what units? How to tune the electronic width of quantum point contacts? Does conductance quantisation resemble the quantum Hall effect in its electron density-change form? What are specific features and accuracy of conductance quantisation in QWR?

8. Describe quantum point contact in an energy-dependent model of one-dimensional leads connected by barrier with transmission probability T. How to calculate the conductance in this model? What is the link between the one-dimensional density of states and the electron velocity? What is total conductance of the ballistic quantum point contact for a mode with T = 1 at zero temperature?

9. What is the conductance of the ballistic quantum point contact for a mode with variable T at zero temperature? What information gives the full conductance of the system about the origin of the quantum of conductance?

10. What is the Landauer formula for the conductance of a multimode quantum point contact? What is adiabatic quantum transport? How is it linked with the scale of the Fermi wavelength and the width of an electron channel?

11. How does the shape of quantum point contact influence the shape of conductance steps? What is the effect of temperature on steps? At what characteristic temperature do steps disappear? Are steps infinitely sharp at zero temperature? What is the form of steps for the saddle-type potential $V(x, y) = 1/2\ m^*(\omega_y^2 y^2 - \omega_x^2 x^2)$? How behave the steps at different $\omega_y^2 y^2$ and $\omega_x^2 x^2$?

12. What is the influence of perpendicular and parallel magnetic field on the conductance of quantum point contacts? What is the behaviour of QPC in weak perpendicular magnetic fields? Explain the nature of diamagnetic shift.

13. Describe the influence of perpendicular magnetic field on two-mode quantum point contact. Is the change of conductance by $4e^2/h$ possible here?

14. Explain transconductance measurements of two-mode quantum point contact in perpendicular and parallel magnetic field. What is the 'lever arm' term related to the effect of gate voltage on the performance of device? What is its typical value?

15. What is the origin of quantised resistance in quantum wires? How to avoid experiencing contact resistance in an experiment? How do potential leads influence contact resistance? What is the result of resistance measurements in a typical arrangement of potential leads?

16. Introduce Landauer–Büttiker formalism. What is it used for? Can it describe current flow in 2D electron gas? Please give an example.

17. What is the origin of resistance quantisation in 2D electron gas? Describe gate-controlled current flow in 2DEG. How do resistances between different contacts depend on filling factors: N in the un-gated region and M in the gated region?

18. Describe the concept of edge channels. Why are the edge channels formed? Does electron screening in metallic regions play role in their formation?

19. What do other quantum-wire or point-contact systems, except semiconducting, you know? Does conductance quantisation take place there? Please give examples.

20. Can carbon nanotubes be used as quantum wires? How would you classify carbon nanotubes? What applications of carbon nanotubes do you know?

21. Can you give examples of the use of quantum wires and quantum point contacts in an electronic circuitry? What kind of effects do appear in these circuits? How to describe circuit's behaviour and what formalism is useful in this description?

Questions to Chapter 8 ‘Electronic Phase Coherence’

1. Describe Aharonov–Bohm effect. How is it possible that a charged particle is affected by magnetic field in a region where magnetic field is absent? What characteristic length is important for this effect? Does it take place in diffusive regime? What value does oscillate in this effect and with what period?

2. What is the difference between Aharonov–Bohm and Altshuler–Aronov–Spivak (AAS) oscillations? Can you explain both in ring geometry? What oscillations supposed to survive ensemble averaging and why?

3. Describe experimental realisations of Aharonov–Bohm and Altshuler–Aronov–Spivak (AAS) oscillation effects. What could be concluded from the experiments? Why are small sizes and low temperatures needed in these experiments?

4. What is weak localization? Is the resistance enhanced or reduced in coherent, as compared to the incoherent case? Can you explain why? At what magnetic fields takes this effect place?

5. What role plays time reversal trajectories in weak localization? How magnetic time and phase coherence time are mixed in weak localization? What weak localization experiment do you know? What temperature dependence of the phase coherence time is found in the experiment?

6. What are specific features of universal conductance fluctuations? Do they need phase coherence of electrons? Why are they frequently referred to as parametric fluctuations?

7. What is the variance of conductivity for universal conductance fluctuations? Do fluctuations characterize the specific impurity configuration? Are they linked with weak localization and do localization loops play role in UCF?

8. Does average universal conductance fluctuation amplitude depend on sample size, strength, configuration and number of the elastic scatterers? Why are these fluctuations named universal? What do UCF depend on?

9. What theorem are theoretical models describing parametric UCF based on? Describe the principle of ergodicity.

10. What conclusions can be drawn from the observations of universal conductance fluctuations in quantum wires with shifted parabolic potential? Are UCF caused just by the large-angle scatterers that determine mean free path (l_e)?

11. Is electrostatic Aharonov-Bohm Effect possible? What is the phase shift in this effect?

12. Describe an experiment to test the phase coherence in ballistic 2DEGs. What is the phase shift that the electrons acquire underneath the control gate of a width

W assuming a linear relation between the gate voltage V_G and the Fermi energy E_F in the 2DEG? Define V_T as the voltage that completely depletes electron density below the gate.

13. What conclusions can be drawn from the experiments on ballistic point contacts connected in series and controlled by the depleting gate? How could coherence length and time be found? What are their values in ballistic point contacts? What is the origin of electron dephasing?

14. What is advantage of tunnel barriers comparable to direct resistive nanostructures? Is electron coherence possible in tunnel structures? What is the difference between classical motion and quantum tunnelling? Please describe transmission of an electron through the tunnelling barrier in terms of wave functions.

15. What is the expression for the transition probability of a single rectangular tunnelling barrier? Please describe tunnelling regime and over-barrier transmission. What are their criteria?

16. Introduce tunnelling S-matrix for a single rectangular tunnelling barrier. What are reflection and transmission terms? What are the unitarity conditions for the matrix?

17. Introduce the double barrier tunnelling problem. What is the transmission probability for the double barrier structure as function of transmission and reflection in individual barriers? Give the condition of resonant tunnelling.

18. Describe resonant tunnelling of the double barrier structure. Is it possible that transmission of double barrier is higher than transmission of individual barriers in series? Would it be possible to fit resonance curves with Lorentzian? Do you know resonant tunnelling analogue in electro-magnetism?

19. What is the attempt frequency and partial escape rate for the double tunnelling barrier structure? Can you write the transmission probability for the double barrier junction in terms of energy and partial escape rates of individual barriers?

20. Can you outline the description of the transmission through a ballistic quantum ring in terms of S-matrix and the transmission through a ballistic quantum ring locked between two tunnel barriers, using Shapiro matrix? What is the transmission of an ideal quantum ring as a function of dynamic θ and magnetic ϕ phase for different reflection amplitudes at the ring entrances?

Questions to Chapter 9 'Single-Electron Tunnelling'

1. Explain why just single electron can influence conducting properties of material on nanometre scale. Is charging effect of an island through which electron is passing important?

2. What is Coulomb blockade? What conditions need to be satisfied to observe Coulomb blockade?

3. What is a single-electron transistor? Please compare energy of transistor with N and N+1 electrons on the island. What is the energy condition for changing the number of electrons in the transistor? At what gate voltage can it take place?

4. What is the influence of environment on the state of an island with electrons? Is environment important? Introduce the background (or induced) charge of the device. At what background charge does the difference in the energy of an island with N and N+1 electrons vanish?

5. Is environment resistance strongly influencing a single tunnel junction device? What does it look like in experiment? At what environment resistance is the Coulumb blockade well-pronounced in a single-electron device? How to relax the influence of environment?

6. What is the capacitance matrix formalism for a basic single-electron tunnelling circuit? Please introduce island charge and potential vectors. How these scalar parameters can be vectors? How to treat single-electron tunnelling circuits? What is condition of the transition of the electron system to a new ground state? Can you describe terms of the basic equation that is used to analyse the motion of electron between island, source and drain?

7. Describe the double-barrier single-electron device. What is its equivalent circuit? Formulate its capacitance matrix. What is the condition of the transfer between states of this device? Analyse simplest situation of zero voltage,

zero background charges and zero number of electrons on island. Is Coulomb blockade possible in this case?

8. Consider double-barrier single-electron device with an applied voltage in a simple situation of zero background charges and zero number of electrons on island. What is the condition of Coulomb blockade in this case? Describe the process of cycled transfer of electrons.

9. What is the influence of background charge on the electron transfer in double-barrier single-electron device? Can background charge increase or reduce Coulomb gap? At what condition does Coulomb gap vanish completely?

10. How to take into account the change in energy ΔE during a tunnel event in a mesoscopic structure that has a transition rate Γ(ΔE)? What is the Fermi Golden rule?

11. How to calculate current–voltage characteristic of the double-barrier structure in a steady state taking into account change of the energy of electron during the tunnelling? How is Coulomb blockade expressed in current–voltage characteristic? What is staircase current–voltage characteristic? What is the condition of its appearance in the double-barrier structure? What is the island-charge period in staircase? Suggest a qualitative explanation of the staircase effect. Can scanning tunnelling microscope be used to measure staircase effect? Please explain how.

12. Explain the principle of single electron tunnelling transistor (SET). What is its schematic diagram? How does gate voltage influence Coulomb gap? Draw the 'diamond'

stability diagram of a single-electron transistor. What is on its axis? How does system behave inside and outside of diamonds?

13. Was current-voltage characteristic of single electron tunnelling transistor first measured experimentally? At what source-drain voltage do Coulomb blockade oscillations take place? What changes by one in each gate voltage period in Coulomb blockade oscillations? Was Coulomb staircase also seen in single electron tunnelling transistor? Why could it appear there?

14. Give example of a typical mesoscopic structure in which Coulomb blockade oscillations take place. Does current there represent a single energy-level state? Is the peak in conductance temperature-dependent? Why is it said that Coulomb oscillations measure not the density of states on the island, but the addition spectrum? What is added?

15. What is single electron transistor with Coulomb blockade oscillations sensitive to? Can it be used as an electrometer? In what device? What is its expected sensitivity? What is the advantage of single electron transistor compared to other mesoscopic devices? Can it be used at room temperature? What are its limitations and how, in principle, could they be overcome?

16. What is the necessity for introducing a resistively coupled single-electron transistor? What is its schematic diagram? How does it work and what is its difference from SET? Does the gate voltage able to keep the island potential fixed for a long time? Does device have single or multiple ‘diamonds’? Do Coulomb blockade oscillations take place

here? Does device very sensitive to fluctuating background charges? What are its main disadvantages comparable to SET?

17. Describe a two-island, two-gate single electron transistor. What is its ground state as function of two gate voltages at zero and finite capacitances between islands? Are any points in the stability diagrams at which current could pass from source to drain? How can charge configuration of the double-island system be directly monitored and what is the result of this monitoring?

18. How does the stability diagram of two-island, two-gate single electron transistor change in the presence of nonzero bias voltage? What is the principle of electron pump operation? What is the link between the current on the plateau of the diagram and the frequency of AC signal added to the gate voltage?

19. Can double-island system be used as current standard? What is its current accuracy? How accurate is the number of electrons pumped? What is the co-tunnelling and how can it be prevented? How to make the capacitance standard? What could be its standard deviation?

Questions to Chapter 10 'Quantum Dots'

1. How can quantum dot be defined? What characteristic wavelength plays main role in its definition? Please explain why. Compare properties of quantum dots with properties of atoms. What holds electrons together in

quantum dot? How can the number of electrons in quantum dot be changed? What are main applications of quantum dots?

2. Describe lateral quantum dot. What is the conductance as function of voltage between its different electrodes? How to disconnect central area of QD from the environment?

3. Oscillations of what parameter are observed in quantum dots as a function of gate voltage? What could be the nature of these oscillations? What effects play major role in their appearance?

4. What are distinctive regimes in the voltage position of conductance oscillations as function of magnetic field that are typically observed in QDs? What could be the origin of their specific features in these regimes?

5. What is the shape of conductance oscillations in QD? Does it resemble Coulomb blockage oscillations? Could this effect be described by the diamond stability diagram for the Coulomb-blockade single electron transistor? How does amplitude of oscillations depend on magnetic field?

6. Explain main assumptions of constant interaction (CI) model. Define the distance between the energy levels in 2D quantum dot. How does it depend on the area of QD? What is other energy scale that is important for CI model? How to calculate the addition energy of one electron to QD? How to modify single-electron tunnelling model to get CI model? What does constant interaction model not take into account?

7. Describe Fock-Darwin model. What are its assumptions about the shape of QD and confinement of its electrical potential? What is the result of Schrödinger equation solution for this model and what are natural quantum numbers that are used to express this solution?

8. Introduce the j^{th} Fock–Darwin shell. Illustrate splitting of Fock–Darwin levels by magnetic field. How is it reflected in experimentally observed behaviour of conductance peaks in low magnetic fields?

9. Explain the behaviour of conductance peaks in intermediate magnetic field. Introduce Landau level quantum numbers. How do parabolic potential dot levels transform into Landau levels? Explain switching between Landau levels at occupation numbers between 4 and 2.

10. What is magnetic field period and typical energy spacing in the spectrum of conductance peaks in QD in intermediate fields? How does the picture change in a hard wall-confinement? What is the behaviour that is expected in a quantum ring?

11. Explain Hund's rules for a quantum dot. How would the filling of the Fock-Darwin potential by first 6 electrons at B = 0 take place? Are Hund's rules applicable for filling factor below 2?

12. What happens with conductance peaks at filling factor below 2? Has it anything to do with 'edge channels'? Explain spin separation model for circular dot and the role of intra-dot capacitance.

13. Does quasi-chaotic behaviour take place in quantum dots? If yes, how is it expressed? Is it classical or quantum chaos? What is the difference?

14. Explain main features of the nearest-neighbour conductance peak separation in QD. What are statistical distributions and techniques that could be used to describe it? Are there universal distributions? Is random matrix theory applicable in this case? Can you comment on universal Wigner-Dyson distributions and their applicability to QDs? Does experiment show behaviour different from these distributions?

15. What are approaches that could be taken to explain amplitude and shape of conductance resonances? Can you explain amplitude variation in a simple diagram model of quantised levels for a QD separated by two tunnelling barriers? What is the role of electrostatic charging energy there? How can single-particle levels be determined by high-bias transport measurements? Can shape of resonances be easily analysed?

16. Give examples of other than semiconducting quantum dots. Could they be used as components of molecular electronics? Can nano-crystals be used as QD? Can you give examples of these?

Questions to Nanomechanics

1. What are main branches of Nanophysics? What is the place and role of Nanomechanics there?

2. Give some examples of Nanomechanics devices. What are their functions? Why are they needed? What are the promises of Nanomechanics devices?

3. Describe Flexural Resonators. What are their main types? What are their typical frequencies and quality factors? How is possible to control their parameters? What materials are good for their preparation and what techniques are needed for that? How are flexural resonators coupled to external electronic circuitry?

4. How does the frequency of doubly-clamped resonator depend on its mass, length, thickness and Young's modulus? How can it be actuated and sensed?

5. What are Resonant Mass Sensors? Describe principle of their work. How does minimum detection mass depend on the mass of resonator, its frequency and quality factor? What is the sensitivity of resonant nano mass sensors? Can it be compared with 1 Dalton? What is the principle of biomolecular recognition?

6. Describe the geometry and the principle of work of tunable carbon nanotube electromechanical oscillators. What are their resonance frequencies? How do actuation and detection of nanotube motion achieved? What are different regimes of oscillations and their oscillation modes? How could motion of nanotube be detected?

7. Can monolayer graphene be used in nanomechanical resonators? What could be advantage of graphene comparable with other materials? Describe a model that could be used to describe these resonators. How do their

frequency and quality factor change with cooling? What could graphene resonators be used for?

8. How can displacement be sensed with the help of single electron transistor? Describe the geometry and principle of work of a relevant device. What is its noise-limited sensitivity? Is it comparable with the radius of proton?

9. Describe possible quantum behaviour of mechanical resonator. Can resonator operate near the ground state of motion? What is the benefit of connecting it to the Superconducting Microwave Resonator? What is the principle of parametric cooling? Can you describe it in terms of parametric amplification? What are occupation factors already achieved by cooling? What is resonator motion sensitivity comparable with quantum length-scale of the device? What is the typical value of the latter?

10. Give an example of nanometer-scale mechanical electrometer. What is the principle of its readout? What could be its advantage comparable with single electron transistor?

11. Describe a nanoscale bolometer. What is the advantage of its small volume and principle of suspension? What kind of thermistor element may it use?

12. Describe longitudinal and flexural vibrations of a strained nano-beam. What is the difference between longitudinal and flexural deformations? How do resonanse frequency depend on the length of the beam in these cases?

13. Describe principle of electron shuttle. How can it be realised experimentally in a quantum ‘bell’ or C_{60} transistor configurations? Is tunnelling involved in this process?

14. What is principle of work of tuning fork resonator? How can it be set in motion? What can it be used for?

15. Describe an optomechanical device. What is the principle of the enhancement of the mechanical effects of light? How is cavity’s resonance frequency influenced by the displacement of cantilever?

16. Comment on near-field cavity optomechanics devices linked with nanomechanical oscillators. Do they allow quantum-limited position measurements or enable amplification and cooling of mechanical motion? Can they be used as readout techniques for quantum nanomechanical motion? Are there any chances of using them at room temperature?

Questions to Nanophotonics

1. Why light is of particular interest for nanophysics?

2. What are main features of the interaction of light with nano and micro particles? Could you describe scattering of light by molecular dipoles, insulating, semiconducting and metal nanoparticles? What are specific features of light scattering on particles with dimensions on the order of its wavelength or bigger?

3. Give examples of nano application in generation and transmission of light.

4. What limitation in resolution sets Abbe diffraction limit? What are the numerical aperture and optical resolution in comparison with wavelength of light? Is it possible to overcome diffraction limit in imaging?

5. Explain principle of super-resolved fluorescence microscopy (Nobel Prize in Chemistry 2014) that 'brought optical microscopy into the nanodimension'.

6. Describe resonance scattering of light by a harmonic oscillator. To what power of frequency is proportional the intensity of scattered light? Does scattering occur in backward direction only?

7. What are specific features of non-resonant scattering on O_2 and N_2 molecules or insulating nanoparticles? Why sky is blue and clouds are white?

8. Explain bandgap value and photoluminescence frequency dependence on the size of semiconducting nanoparticles. How can one vary size of semiconducting nanoparticles?

9. Give examples of the use of metallic and semiconducting nanoparticles in art of visual effects and biomaterials tagging.

10. Describe Drude model of the dielectric function in a metal. Why are metals shiny? What is cut-off frequency for total reflection?

11. Give example of cut-off frequency use in energy saving window nano-coatings.

12. Describe the plasmon resonance. What technique is usually used for observation of bulk and surface plasmons? How the energies of bulk and surface plasmon modes are related to each other?

13. Introduce relative to the medium dielectric function and describe quasi-static Rayleigh theory in application to nanoparticles. What are condition of resonance and the calculated resonance energies for silver and gold nanoparticles in vacuum and a polarizable media? What are the limits and problems of this electrodynamic description?

14. Describe peculiarities of the light scattering by nanoparticles with size d $\ll\lambda$, d $\approx\lambda$ and d $\approx 2\lambda$. In what case there is very strong forward scattering and peaks corresponding to different colours? What happens with light-matter interaction when size of particles (in particular spheres) goes above the nanometer scale?

15. Introduce photonic crystals. What are they used for and what is the similarity in their behaviour with the behaviour of electron in a crystal? Can they be used as biosensors? If yes - how? Give examples of artificial and natural photonic crystals.

16. Describe mathematical similarities between electromagnetism and semiconductor physics, electromagnetism and quantum mechanics. What does Bloch theorem for electromagnetism state? Does it lead to

band structure? Can, as a result of the band structure, light be slowed down and stopped?

17. What are principal limitations for bit-rate of signals in electronics and photonics? What are advantages of plasmonics? Describe bulk and surface plasmon excitations. What is their dispersion relation? Why surface plasmons are often referred to as "X-rays" with optical frequencies?

18. Describe principle of work of the quantum cascade laser. Draw an energy diagram of it. What could be the role of inter-sub-band transitions and optical phonons there? How to provide a well-defined wavelength in a distributed-feedback quantum cascade laser?

Questions to Chapter 11 'Mesoscopic Superlattices'

1. Give examples of mesoscopic superlattices. Describe methods of their preparation. What could be dimension and spatial resolution of practically useful superlattices? What new physics and unusual features would one expect in superlattices?

2. Describe Weiss oscillations. What is their periodicity in magnetic field? In what kind of superlattices do they take place? Are they anisotropic?

3. How can small electron density modulation lead to strong Weiss oscillations? Give semiclassical description of the oscillations by introducing cyclotron orbits and analysing local drift of electrons.

4. Give example of a two-dimensional superlattice. What are antidot lattices and their commensurate fields? How can commensurate fields result in increased resistivity?

5. Introduce an approach to analyse Hall Effect and longitudinal resistance in antidot superlattices. What is realistic potential for electrons in isotropic and anisotropic antidot lattices and how it affects the resistance?

6. Describe technique of Poincaré sections. How can they shade light on the evolution of electron motion? Does bias voltage mix the chaotic and regular regions of the phase space? Is it correct that electrons in the regular regions are main carriers of current?

7. Can description of conductance be given using a diffusion model? Is Kubo formula applicable in this case? Can you comment on classical and quantum Kubo formulae? What is the diffusion coefficient in the Kubo formula in an absence of magnetic field and driving force?

8. Can quantum effects be seen in the behaviour of superlattices in strong magnetic field? Does anything unusual happen in hexagonal antidot lattice? If yes, can you give possible quantum interpretation of the effect?

9. Describe the 'Hofstadter butterfly' effect and the lift of degeneracy in the Landau fan by weak periodic potential. How is 'Hofstadter butterfly' reflected in transport properties of superlattices?

10. Explain the action of superstructure in quantum cascade structures. How is it utilised in quantum-cascade lasers?

11. Give examples of periodic optical nanostructures. Describe the structure and possible applications of photonic crystals.

Questions to Chapter 12 ‘Spintronics’

1. Explain what electron spin is. Introduce magnetoresistance. Give example of magnetoresistance in a material or system. What is role of electron spin in magnetoresistance of materials? What is spintronics?

2. Give examples of spintronics applications. What is spintronics advantage comparable with conventional (charge) electronics? Why could spin be more effective than charge?

3. Is orbital magnetoresistance large in typical metals at room temperature? How does xx component of longitudinal resistance depend on field in two-dimensional electron gas? Can you derive its value from the conductance matrix?

4. Introduce effect of tunnelling magnetoresistance (TMR). What are the materials suitable for tunnelling magnetoresistance devices? Explain how TMR works and how to make tunnel magnetoresistance junctions. What are current and expected applications of TMR?

5. What is spin polarization? Write its expression. What is effect of spin polarization on tunnelling magnetoresistance? Is tunnel resistance lower for antiparallel alignment of spins?

6. Link conductance and polarization. How is tunnelling magnetoresistance (define it) expressed through the polarization of source and drain? Give an example of ideal TMR value for a metal, for instance, cobalt.

7. Explain how tunnelling magnetoresistance can be used in memory chips? Is hard ferromagnetic layer necessary in their construction? Is yes, why? How to assemble a sequence of TMR elements and how to write and read information? Are movable parts necessary? Are stored data lost when the power is turned off?

8. Introduce phenomenon of giant magnetoresistance (GMR). In what systems does it take place? What are materials suitable for GMR devices and how are they used? What is the difference between GMR and TMR?

9. Introduce Mott's two-current model for giant magnetoresistance. What is the role of interfaces and their resistances in GMR?

10. Explain the concept of itinerant magnetism. Does itinerant magnetism important for giant magnetoresistance? In what materials does it takes place and what orbitals are most important for this effect? What role does exchange interaction play in itinerant magnetism? What is the Stoner criterion for ferromagnetism? Do you know a metal, which is on the verge of ferromagnetism?

11. How do different spin states influence resistance of a material? How do 4d-electron states contribute to the resistance? What are requirements for building magnetic

superlattices for GMR devices? How to engineer magnetic materials using principle of Friedel oscillations? How do electrons in non-magnetic layers provide coupling between magnetic layers?

12. Explain physics of GMR introducing equivalent circuit diagrams. What is the difference in resistance between parallel and antiparallel orientations? Is any way to enhance GMR using half-metals?

13. Can GMR effect be observed when the current flows parallel to the layers? Explain physics of it. What are current-perpendicular-to-plane (CPP) and the current-in-plane (CIP) configurations? Why is CIP important?

14. Outline principles of spin injection. Describe spin transport in ferromagnet and spin accumulation close to interface with normal metal. Introduce spin-flip scattering time and spin relaxation length. Describe these processes in specific materials.

15. How are chemical potentials of differently polarized electrons linked in the interface? Write expression for the current polarization at an ferromagnet-normal metal interface. What is the condition of perfect injection of spins?

16. Introduce concept of Datta–Das spin transistor. Is it implemented? Does it use semiconductor? What are difficulties in injecting spins into semiconductor and what are possible solutions to overcome these difficulties? How can additional interface resistance in a tunnel barrier structure increase injected spin polarization?

17. How to detect spin-polarized current? Has it anything to do with circular polarization of photons? Can LED p–n type junctions be used for that? Please explain how. Do you know any spin-polarization experiments involving GaAs quantum wells? What polarization was observed there?

18. What are ferromagnetic semiconductors? Do they help to solve the impedance mismatch problem? Can they have spin polarization equal to 1? How it can be achieved? Can $Ga_{1-x}Mn_xAs$ be used as a ferromagnetic semiconductor? What are the results of experiments with this compound?

19. What is Rashba effect? Can you explain its origin? Do you know any experimental observations of the Rashba effect? How could this effect be used in spin based field-effect transistor? What are the conditions for constructing Datta–Das transistor?

20. Introduce spin relaxation and spin dephasing times. What mechanisms of spin relaxation do you know? What is their dependence on Drude scattering time?

21. Explain hyperfine interaction. Where does it take place and what is its importance in spin systems? In what devices could it be most efficient? What are possible applications of hyperfine interaction?

22. Name few modern spintronics trends and explain their importance. Do you aware of spintronics aspects in graphene and topological insulators (TIs)? Is single molecule GMR possible?

23. In what quantum devices could spin be used? Can it be relevant to quantum computing? What are other emerging applications of spintronics? What problems need to be solved in this area?

Questions to Superconductivity

1. What are main properties of superconductors?

2. How could superconductivity be destroyed?

3. Is superconductivity quantum or classical effect?

4. What is the Meissner effect? Is this consequence of zero resistance or not?

5. What is the difference between type-I and type-II superconductors?

6. Does positive energy of the interface between normal and superconducting state lead to quantization of magnetic flux?

7. What are first and second critical fields of superconductor? Are they related to quantization of magnetic flux?

8. Do flux quanta move free in superconductor? What is the pinning? Is pinning important for practical applications?

9. What is critical state of superconductor? Have Bean's model for superconductors anything common with sand-pile model?

10. Can you say anything about critical current flowing in the sample if gradient of magnetic flux is known in bulk superconductor?

11. What is critical temperature of superconductor? How large it could be?

12. What is the mechanism of superconductivity? Is it linked to Fermi or Bose statistics?

13. What is high temperature superconductivity? When it was discovered? In what materials does it take place?

14. What are practical applications of superconductors?

15. What are main techniques for investigating superconductors?

16. Can you describe principle of magneto-optical imaging? Can it be used for investigating superconductors?

17. How does magnetic flux penetrate in superconducting thin films? Is abrupt penetration possible?

18. What is thermo-magnetic instability? What are dendritic flux avalanches? Are these effects linked?

19. What is the physics behind the formation of dendritic flux avalanches? Does it need positive or negative feedback?

20. What are main techniques for investigating dendritic flux avalanches?

21. How could superconductivity be important for renewable energy economy?

Questions to Nanoscale Superconductivity and Superconductivity applications

1. How is superconductivity affected by the size of the sample on nanometre scale? Does superconductivity exist in a sample of any size? What is Anderson Criterion for superconductivity?

2. What is the relation between pairing of electrons and superconductivity? Can the first exist on nanoscale without the second?

3. Describe principle of tunnelling between superconductor and normal metal. What are the implications of this nanoscale phenomenon? What could be role of spin in this process?

4. What is Andreev reflection? On what interfaces does it take place? What is zero bias conductance peak (ZBCP)? On what interfaces can it be suppressed?

5. Comment on spin injection from spin-polarised metals to superconductors. How strong is this effect? What is its typical spin diffusion depth? Can it be used in electronic applications?

6. What is parity effect in superconducting quantum dot and the Coulomb blockade of Andreev reflection? Can parity

be measured at the total number of electrons of about 10^9?

7. Can ‘diamond’ features be seen in stability diagram of a Cooper-pair box? What other features can be seen there? Is it possible to observe crossover from 2e periodicity to e periodicity in the Cooper-pair box?

8. Describe stationary Josephson Effect. What kind of tunneling does it represent? What is its nature and what does its amplitude depend on? How is Josephson Effect linked with the phase of the order parameter of superconductor?

9. Can you derive formula for Josephson Effect by treating overlap of wave functions and introducing small auxiliary magnetic field with vector potential δA, which penetrates the junction?

10. Can you derive expression for current in Josephson interferometer using Ginzburg-Landau equations? What quantum of flux does play role there?

11. Can you derive formula for non-stationary Josephson Effect using an expression for the phase change due to electrical field? What is the difference in this formula for superconductor comparable with normal metal?

12. Describe use of superconductors in electronics. What is superconducting electronics’ advantage comparable with conventional electronics?

13. What are main devices superconducting electronics? Can you give details of one of them?

14. What are main power applications of superconductors and what is the role of nanotechnology in these applications? Please describe in detail one of the applications.

15. What is supergrid and what are its prospects for solving current ecological and energy problems? What could be main superconducting material for the supergrid?

16. How world market for superconductors is expected to growth and what is the role of nanophysics and nanotechnology in this growth? In what areas is the biggest growth expected?