NanoElectronics Exam 23 January 2015
Course code: 193400141

Important: *This exam consists of* ***4 problems****, worth* ***100 points*** *in total. The maximum number of points you can get for each question is indicated. Write down your name on each sheet of paper that you hand in. Make each problem on a separate sheet (or separate sheets).* ***The exam you are about to enjoy is a closed-book exam, i.e. study material of any kind is not allowed during the exam.***

list of physical constants:

Planck constant	$h = 6.6260755 \cdot 10^{-34}$ J·s
Boltzmann constant	$k = 1.380658 \cdot 10^{-23}$ J·K^{-1}
Elementary charge	$e = 1.60217733 \cdot 10^{-19}$ C
Permeability of vacuum	$\mu_0 = 4\pi \cdot 10^{-7}$ T·m·A^{-1}
Bohr magneton	$\mu_B = 9.2740154 \cdot 10^{-24}$ J·T^{-1} [T=J·A^{-1}·m^{-2}]

PROBLEM 1: General Aspects (20 points)

Below, 10 statements (1A-1J) are given. Indicate for each statement whether it is **true** or **false**, and **motivate your answer**.

1A (2 points)
The remanent magnetization of a ferromagnetic element (with uniaxial anisotropy) magnetized along its easy axis is larger than the remanent magnetization obtained along any other magnetization axis.

1B (2 points)
Assume we have conductance quantization through a quantum point contact. When the spin degeneracy of subbands is broken, e.g. by a magnetic field, the conductance is quantized in multiples of $2e^2/h$ instead of e^2/h.

1C (2 points)
The energy bands in organic semiconductors are much narrower than in inorganic semiconductors because of the geometrical relaxation effects associated with charging/neutralizing organic molecules.

1D (2 points)
The formation of magnetic domains in ferromagnets is due to classical magnetostatics rather than the exchange interaction.

1E (2 points)
The period of the first harmonic of Aharonov-Bohm oscillations equals the flux quantum $\Phi_0 = h/e$. Because h and e are constants of nature, the period of AB oscillations appearing in measurements of the conductance versus magnetic field are independent of the ring size.

1F (2 points)
The magnetic field **B** and the auxiliary magnetic field **H**, related via $\mathbf{B}=\mu_0(\mathbf{H}+\mathbf{M})$ where **M** is the magnetization vector, always point in the same direction.

1G (2 points)
In an organic semiconducting molecular crystal, composed of π-conjugated molecules, the conductivity is *only* anisotropic in the band-like transport regime; in the hopping regime the conductivity is isotropic.

1H (2 points)
When a single-electron transistor is in the single-electron tunneling regime, the electron number on the island alternates between N and $N+1$ electrons, even at zero source-drain bias V_{SD}.

1I (2 points)
The attractive and repulsive forces that play a role in the exchange interaction are due to the spin magnetic moments of the electrons.

1J (2 points)
In theory it is possible to observe orbital excited states in a metallic single-electron transistor at 4 K.

PROBLEM 2: Magnetism and Spintronics (30 points)

2A (8 points)

(1) Make a schematic drawing of a spin MOSFET and indicate its components. (2pts)

(2) What are the benefits of a spin MOSFET? (2pts)

(3) What are the 3 basic requirements for a spin MOSFET to work properly? (2pts)

(4) Illustrate the working principle of the spin MOSFET with I_{SD} vs V_{SD} curves (2pts)

2B (6 points)
What is meant by spin transfer torque? Explain the benefits of switching MTJs with spin transfer torque as compared to magnetic field induced switching in conventional magnetic random access memory.

2C (6 points)
Consider two different ferromagnetic materials, denoted FM_1 and FM_2, with similar exchange constants A,

$A_1 \approx A_2 = 1 \cdot 10^{-11}$ J·m^{-1},

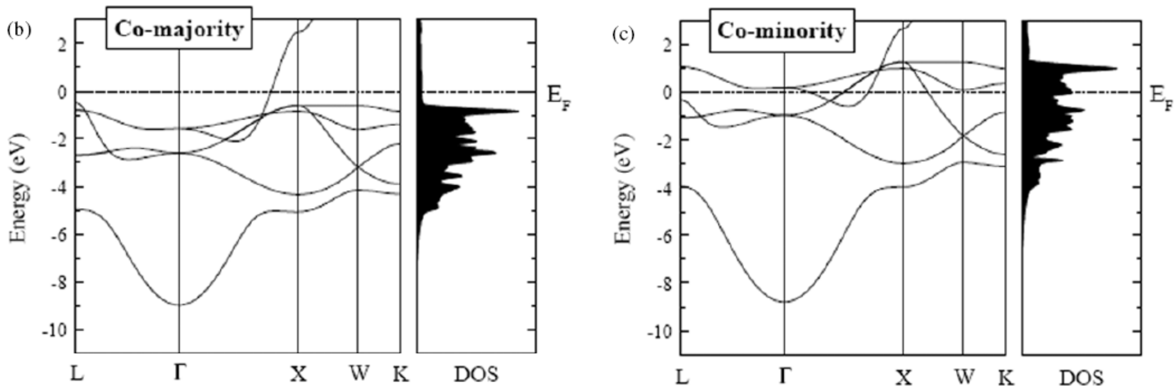
but rather different anisotropy constants K and saturation magnetization values M_S,

$K_1 = 7 \cdot 10^3$ Jm^{-3} and $M_{S,1} = 500$ kA·m^{-1},

$K_2 = 6.3 \cdot 10^4$ Jm^{-3} and $M_{S,2} = 1500$ kA·m^{-1}.

Which material exhibits the widest domain walls? Is this also the material that has the smallest critical diameter d_{crit} (for a spherical particle) at which the transition from a multi-domain to single-domain state occurs? Motivate your answers.

2D (5 points)
Using the figure below, explain why the resistance for majority spin electrons, R_{maj}, and the resistance for minority spin electrons, R_{min}, is different in Co.

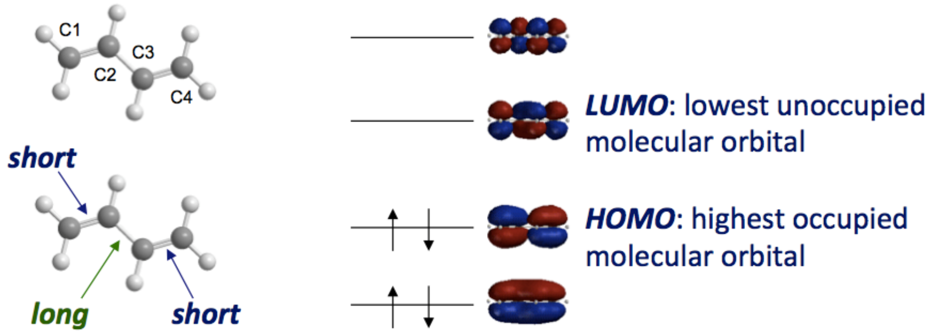


Now consider a Co/Cu/Co spin-valve, consisting of two thin Co layers separated by an ultrathin Cu spacer layer of a few nanometers thick (the magnetization of one of the Co layers is somehow kept fixed).

2E (5 points)
Sketch a spin dependent resistor network that "models" the electrical resistance for current flow through the Co/Cu/Co stack, for two different cases: i) Co layers magnetized parallel, ii) Co layers magnetized antiparallel. You should neglect spin-flip scattering, such that the two current model of N.F. Mott applies. The resistance of the Cu spacer can also be neglected.

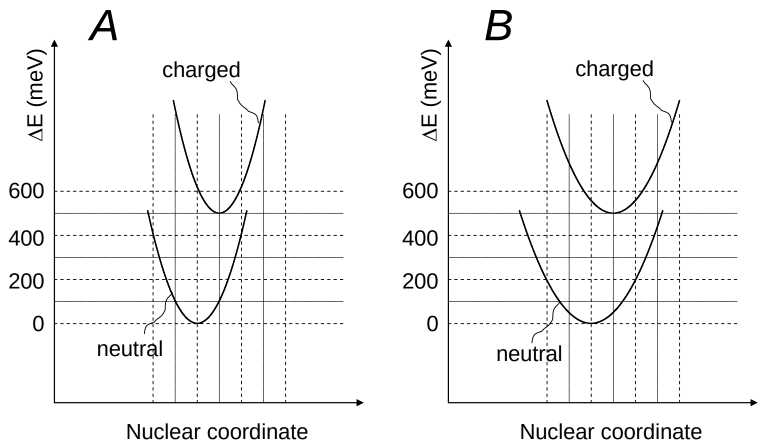
PROBLEM 3: Organic electronics (25 points)

3A (6 points)
Consider the butadiene molecule, with chemical composition C_4H_6, for which the ball-and-stick model is shown below. The relative bond lengths of the carbon-carbon bonds are indicated for a molecule in the *neutral ground state* configuration, with two electrons (represented by the up/down arrows for electrons with spin up/down) occupying the HOMO, and another two electrons occupying the HOMO-1.



Using the nodal pattern of the LUMO as shown (two nodes on the bonds between carbon atoms C1-C2, and between C3-C4), explain what happens to the bond lengths when an additional electron is placed in the LUMO, making the molecule negatively charged. Motivate your answer.

3B (3 points)



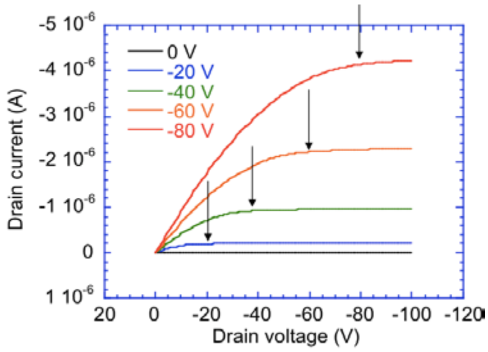
The pictures above show hypothetical energy versus (generalized) nuclear coordinate curves of the neutral- and charged butadiene molecule. In which case is the reorganization energy larger, *A* or *B*? Motivate your answer.

3C (4 points)
Give an estimate of the reorganization energy in the two cases, *A* and *B*.

3D (6 points)
Sketch the layout of an organic thin film transistor, and indicate its main components. Also, give a brief discussion of its main principle(s) of operation.

3E (6 points)

The picture on the right shows the (source-)drain current versus the (source-)drain voltage of an organic thin film transistor, for different gate voltages varying between 0 V and -80 V, as indicated. Explain the relation between the gate voltage and the voltage at which saturation occurs, indicated by the arrows.



PROBLEM 4: Quantum electronics (25 points)

4A (4 points)

Explain two requirements to observe Coulomb oscillations in a single-electron transistor.

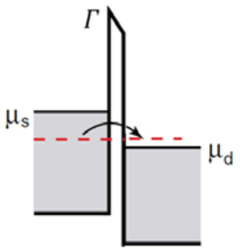
4B (3 points)

A single-electron transistor consists of an island coupled to source and drain reservoirs via two tunnel barriers. A simpler device consists of only a single tunnel barrier with tunnel rate Γ connecting two electron reservoirs with electrochemical potentials μ_s and μ_d, see cartoon below.

(i) Give the expression for the current I as a function of the tunnel rate Γ (1)

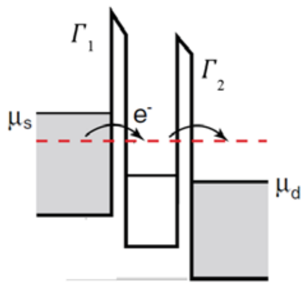
(ii) Calculate the tunnel rate Γ if the current through this single-barrier device equals 1 pA. (1)

(iii) Calculate the typical tunneling time τ of this tunnel barrier. (1)



4C (5 points)

Now we consider a single-electron transistor of which the two tunnel barriers have tunnel rates Γ_1 and Γ_2, see cartoon of the electrochemical potentials below.



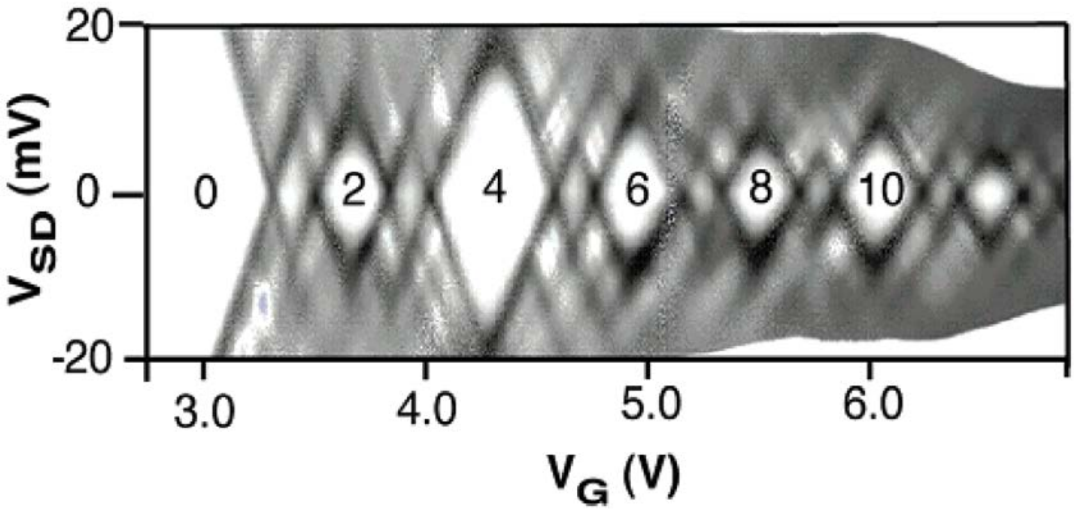
(i) Give the expression for the current I through this device. (1)

(ii) If the tunnel rates are equal ($\Gamma_1 = \Gamma_2$) and the current through the quantum dot is 50 pA, what is the typical tunnel time τ through a single barrier? (1)

(iii) Is it possible to derive the typical tunneling time of barrier 1 and 2 in case of asymmetric barriers ($\Gamma_1 >> \Gamma_2$) and I = 50 pA? If not, what *do* you know about τ_1 and τ_2? (3)

4D (13 points)

Below is a measurement from the article "Few-Electron Quantum Dots in Nanowires" by Björk *et al.* (Nano Letters 4, p1621 (2004)). This plot shows the differential conductance in grayscale versus gate voltage V_G and source-drain voltage V_{SD}. Numbers in diamond shaped regions indicate the electron occupation number of the quantum dot.



(i) Indicate the following regions either in a self-made sketch or in the cartoon above. Make the borders of the regions unequivocally clear.

a. Coulomb blockade region(s) (CB) (1)

b. Single-electron tunneling region(s) (SET) (1)

c. Double-electron tunneling region(s) (DET) (1)

(ii) Estimate the capacitance of the gate C_G and show/explain clearly how you extracted it. (2)

(iii) Estimate the charging energy E_C in meV and show/explain clearly how you extracted it. (2)

(iv) Estimate the addition energies E_{add} of the 2nd, 3rd, 4th and 5th electron and show/explain how you extracted them. (2)

(v) Explain the pattern in the Coulomb diamond sizes. (2)

(vi) Estimate the orbital level spacing $\Delta E_{1\text{-}2}$ between first and second orbital and the orbital level spacing $\Delta E_{2\text{-}3}$ between second and third orbital. Show/explain clearly how you extracted it. (2)

END OF EXAM