NANOELECTRONICS.

NanoElectronics Exam 27 January 2014

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 <u>closed-book exam</u>, i.e. study material of any kind is <u>not</u> 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, 8 statements (1A-1H) are given. Indicate for each statement whether it is **true** or **false**, and **<u>motivate your answer</u>**.

1A (2 points)
The magnetic field **B** and the auxiliary magnetic field **H**, related via **B**=μ_0(**H**+**M**) where **M** is the magnetization vector, always point in the same direction.

1B (3 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.

1C (3 points)
The remanent magnetization of a ferromagnetic element (with uniaxial anisotropy) magnetized along its easy axis is smaller than the remanent magnetization obtained along any other magnetization axis.

1D (2 points)
Magnetic nanoparticles for which the anisotropy constant is small have a higher thermal stability (longer magnetization reversal time) than similar nanoparticles with a large anisotropy constant.

1E (3 points)
In magnetic tunnel junctions, the magnitude and sign of the tunnel magnetoresistance depend only on the ferromagnetic contacts used, and not on the tunnel barrier.

1F (2 points)
When a single-electron transistor is in Coulomb blockade, the electron number on the island alternates between N and $N+1$ electrons.

1G (3 points)
Orbital excited states cannot be observed in a metallic single-electron transistor.

1H (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.

PROBLEM 2: Magnetism and Spintronics (30 points)

2A (10 points)

(1) Make a schematic drawing of a spin MOSFET and indicate its components.
(2) What are the benefits of a spin MOSFET?
(3) What are the 3 basic requirements for a spin MOSFET to work properly?
(4) Illustrate the working principle of the spin MOSFET with I_{SD} vs V_{SD} curves

2B (5 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 (5 points)
The formation of magnetic domains results from competing mechanisms. Give a brief description of each of these mechanisms, and indicate which mechanism promotes/hinders the formation of magnetic domains.

2D (5 points)
Explain the difference between giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR) as precisely as possible.

2E (5 points)
Consider two different ferromagnetic materials, denoted FM_1 and FM_2, with similar exchange constants A,

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

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

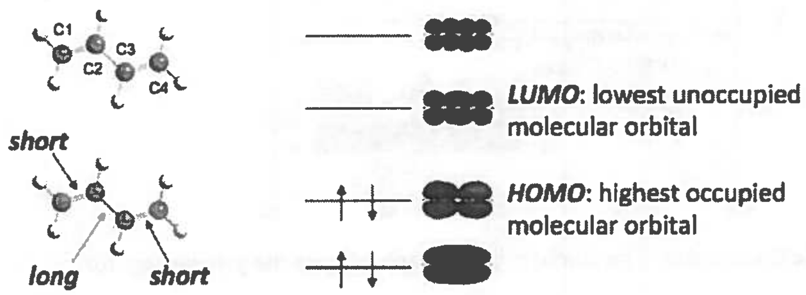
$K_1 = 7\cdot 10^3\ \mathrm{Jm^{-3}}$ and $M_{S,1} = 500\ \mathrm{kA\cdot m^{-1}}$,

$K_2 = 6.3\cdot 10^4\ \mathrm{Jm^{-3}}$ and $M_{S2} = 1500\ \mathrm{kA\cdot m^{-1}}$.

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.

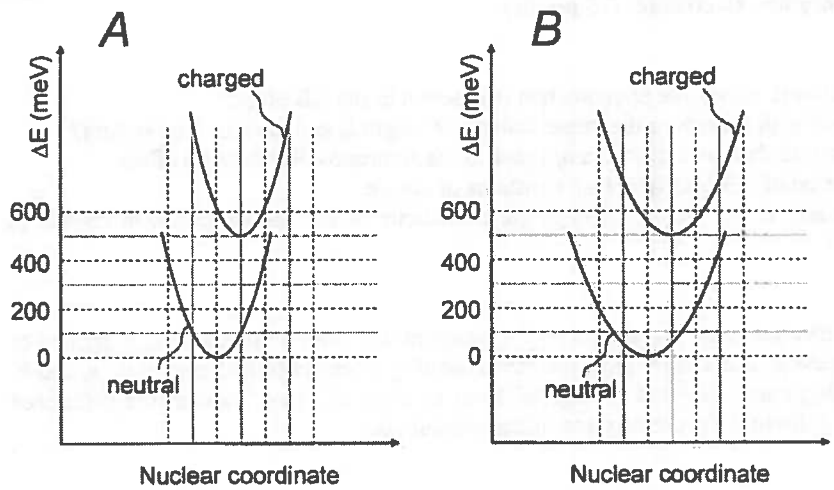
PROBLEM 3: Organic electronics (25 points)

3A (5 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.

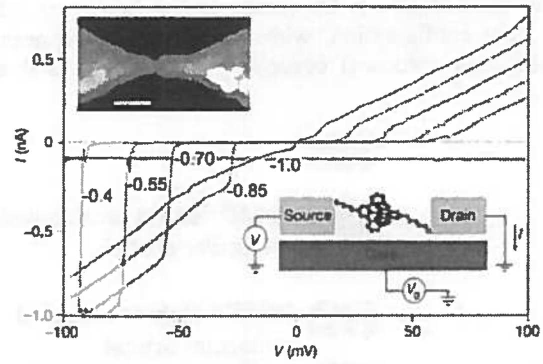
3B (5 points)



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

3D (5 points)
Is it conceivable that, in a certain organic crystal, charge transport would occur via hopping for electrons, while it is band-like for holes? Discuss.



I-V curves of a single Co complex. The numbers in the graph indicate the gate voltage for each curve in volts.

3E (5 points)
See the figure above. What is the voltage gain of this molecular transistor at $I = -0.1$ nA?

PROBLEM 4: Inorganic electronics (25 points)

4A (5 points)
(a) Which non-classical, wave-like phenomenon is inherent to the AB effect?
(b) What is required with regards to the phase coherence length l_φ and the size L of system?
(c) Explain how the conductance quantum *appears* in the Aharonov-Bohm (AB) effect.
(d) Express the period of AB oscillations in constants of nature.
(e) How does the size L of system influence the periodicity of the oscillations with respect to magnetic field?

4B (5 points)
Sketch the electrochemical potential diagram of a quantum dot, with a voltage bias V applied to source or drain reservoir, and clearly label the corresponding electrochemical potentials μ, and V. Indicate the charging energy E_C and the orbital level spacing ΔE. Last, explain the difference between available states in the reservoirs and in the quantum dot.

4C (5 points)
Give the expression for the current I through a quantum dot with tunnel rates Γ_1 and Γ_2 for barrier 1 and 2. If the tunnel rates are equal ($\Gamma_1 = \Gamma_2$) and the current through the quantum dot is 100 pA, what is the time τ it takes to pass a single barrier? Can you derive that time for barrier 1 and 2 in case of asymmetric barriers ($\Gamma_1 >> \Gamma_2$) and $I = 100$ pA? If not, what *do* you know about τ_1 and τ_2?

4D (10 points)
Sketch the stability diagram of a quantum dot, i.e. the differential conductance versus gate voltage V_G and source-drain voltage V_{SD}. Assume that the magnetic field $B = 0$. Indicate in your sketch:

- Coulomb blockade region(s)
- Single-electron tunneling region(s)
- Double-electron tunneling region(s)
- The charging energy E_C and the orbital level spacing ΔE.
- Electron number $N+1$, N, $N-1$

END OF EXAM