POLITECNICO DI TORINO

Advanced Experimental Physics

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[with contributions from E. Piatti and M. Cagnoni]

A. A. 2024-2025

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Motivations:

- Applications of models (theory) to experimental results in solid-state physics
- Experimental training (how the properties of materials can be measured)
- Team building and group working
- Problem-solving approach
- Scientific article writing
- Training in the use of AI in the context of scientific research

Changes from last year: reduction of theory hours, anticipation of laboratories and increase of hours, simplification of the exam

Hours' planning:

- Lessons: $\sim$ 40 h
- Lab activities: $\sim$ 20 h

Laboratory groups: **4 groups** (A, B, C, D) of 6 students each

Materials under study (2025): 1 material for 2 groups

- **Nb** (thin films) → standard metal and superconductor
- **B-doped diamond** (thin films) → hole-doped insulator

Laboratory planning (for each group):

- Instruction and training on experiment # 1 (3h)
- Experimental measurements (experiment # 1, 3h)
- Instruction and training on experiment # 2 (3h)
- Experimental measurements (experiment # 2, 3h)
- DFT training and data analysis ($\sim$ 3 h + 3 h)

Type of experiments (2025):

- Scanning Probe Microscopy at room T (AFM, KPFM, etc …)
- Resistivity vs. Temperature (down to $\sim$ 1.6 K)
- Magnetoresistance at low T (up to $\sim$ 6 T)
- Hall effect measurements at low T

Theoretical computational activity:

- ab-initio Density Functional Theory (DFT) calculations of the electron, phonon and electron-phonon (superconducting) properties of the 2 materials

… more in detail

Nb thin films (groups A and B)

- resistivity vs. T in van der Pauw configuration (θ_D, T_c, λ_{tr}, λ_{sup}, mobility, Ioffe-Regel parameter etc.)
- AFM (thickness, grain size, fractal analysis, etc.)
- resistivity vs. T in magnetic field B in supercond. state (critical field $H_c(T)$, vortex phase diagram, coherence length, etc.)

B-doped diamond films (groups C and D)

- resistivity vs. T (metal-insulator transition, VRH vs. QCM, etc.)
- AFM (thickness, grain size, fractal dimension, etc.) + KPFM (Fermi level)
- resistivity vs. B at low T (magnetoresistance) + Hall effect (charge carrier density)

Exam:

- Preparation of a **group report** in the form of a *scientific article*
- Our **feedback on a preliminary version** and possible update of the report
- **Evaluation of the final report** + **group discussion of the results**

Course material

- **Slides of the course**
- H. Ibach and H. Lüth, Solid-State Physics, Springer, 4^{th} edition, 2009
- N. W. Ashcroft and N. D. Mermin, Solid State Physics, Sauders College, 1976
- U. Mizutani, Introduction to the electron theory of metals, Cambridge Univ. Press, 2004
- G.K. White and P.J. Meeson, Experimental Techniques in Low-Temperature Physics, Oxford Science Publications, Clarendon, 2002
- F. Pobell, Matter and Methods at Low Temperatures, Springer, 1996

Program and calendar

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- **Introduction** (1.5 hrs)

- **Brief survey of solid-state physics** [February, 25th - March 13th]

  1) Crystalline structures, lattices and reciprocal space (1.5 hrs)
  2) Free-electron gas, energy bands and Fermi surfaces (4.5 hrs)
  3) Lattice vibrations (3 hrs)
  4) Hartree-Fock model, correlations and screening (3 hrs)

- **Density Functional Theory (DFT): an introduction** [March 18th - April 1st]

  1) DFT theory and applications (9 hrs)
  2) ABINIT Hands-On (3 hrs)

- **Experimental activity with the groups** [April 3rd - April 17th]

  1) Lab training on experiments #1 and #2 (6 hrs per group)
  2) Experiment #1 and #2 for every group (6 hrs per group)
  3) Specific training on DFT calculations for every material (3 hrs per group)

- **The experimental methods and the theory for the analysis of the results** [May 6th - May 22nd]

    1) Cryogenic techniques and high magnetic field
    2) Atomic Force Microscopy and related scanning probe techniques
    3) Transport measurements: theory and practice (resistivity, magnetoresistance and Hall effect)
    4) Quantum transport in special conditions: superconductivity
    5) Quantum scattering and effects of disorder (metal-insulator transitions, weak localization, strong localization, …)

- **Summary and final remarks on data analysis** [May 27th - June 5th]

    1) Summary and hints on data analysis (3 hrs per material)
    2) Free hours for data analysis with our support (3 hrs per material)