ELEC9705
Quantum Devices

Course Outline – Semester 1, 2015

Never Stand Still | Faculty of Engineering | School of Electrical Engineering and Telecommunications

Course Staff

Course Convener / Lecturer:

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Consultations: You are encouraged to ask questions on the course material before, during and after the lecture class times. Alternatively, questions can be asked via email or during prearranged consultation times. ALL email enquiries should be made from your student email address with ELEC9705 in the subject line; otherwise they will not be answered.

Keeping Informed: Announcements may be made during classes, via email (to your student email address) and/or via online learning and teaching platforms – in this course, we will use Moodle https://moodle.telt.unsw.edu.au/login/index.php. Please note that you will be deemed to have received this information, so you should take careful note of all announcements.

Course Summary

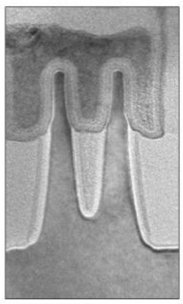
Contact Hours

The course consists of one 3 hour lecture each week. There will be no laboratories or tutorials.

Lectures	Day	Time	Location
	Thursday	6 pm – 9 pm	Central Lecture Block, CLB 4

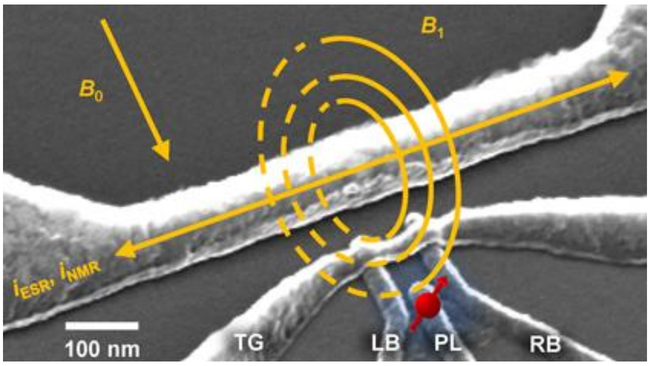
Context and Aims

The progress of nanotechnology allows the fabrication of devices whose physical dimensions are approaching the atomic scale. The figure on the right shows an electron microscope image of the cross-section of a state-of-the-art transistor, as found in every modern computer and mobile phone. The width of the transistor channel is 14 nm, that is, ~25 atoms across. In undergraduate electronics courses, you have learned how to design circuits that use transistors for amplification, logic operations, etc… and you never needed to know anything beyond simple circuit rules to do so.



14 nm 2nd Generation Tri-gate Transistor

Since over 100 years, it has been known that the behaviour of physical systems at the atomic scale does not obey the familiar laws of classical physics. Atomic-size systems behave according to Quantum Mechanics, which allows them to exhibit rather spectacular properties and dynamics. But what happens when nano-engineered devices approach the atomic scale? The figure on the right is an electronic device fabricated at UNSW using silicon microelectronics techniques. But it is not just a transistor. It is a ‘quantum bit’ that can store and manipulate information encoded in the quantum state of a single atom inserted in the silicon chip.



Designing and operating devices that behave according to Quantum Mechanics opens the possibility to exploit the peculiar laws of quantum physics to perform otherwise cumbersome or impossible tasks. These include the efficient solution of computationally hard problems, or the secure teleportation of information. Examples of computationally hard problems can be found in all branches of science and technology – including medical research.

It should also be noted that even classical electronic devices like state-of-the-art transistors are designed using deep understanding of quantum mechanics. In a 14 nm wide transistor, great care must be used to prevent the electrons from travelling straight across the channel by means of a phenomenon called “quantum tunneling”! Therefore, a good understanding of the role of Quantum Mechanics in modern devices is becoming an increasingly essential knowledge set for modern engineers.

The aim of ELEC9705 Quantum Devices is twofold:

- Give a succinct introduction to Quantum Mechanics, with an emphasis on the basic concepts and a selected range of quantitative techniques to analyse quantum systems;
- Describe the working principles of nano-engineered devices that are designed to be the building blocks of future quantum information and communication systems.

The relevance of Quantum Mechanics in advanced electronic devices will be illustrated by discussing in detail several practical examples:

- Single-electron transistor - the most sensitive electrometer, capable of detecting the displacement of a single electron charge in its vicinity;
- Quantum point contact - an electrical conductor with cross-section comparable to the electronic wavelength;
- Superconducting Quantum Interference Device - the most sensitive magnetometer, able to detect a fraction of a magnetic flux quantum;
- Charge, phase, and flux qubits - micron-size electrical circuits that can be prepared in a macroscopic quantum superposition of different states;
- Quantum dots - also known as “artificial atoms”: nanostructures that confine a small number of electrons and allow the preparation and observation of their charge and spin states.

The course will ideally prepare the students to participate in advanced post-graduate research projects, or work in specialized industries with high involvement in research and development.

Indicative Lecture Schedule

Period	Summary of Lecture Program
Week 1 (5.3.2015)	Introduction
Week 2 (12.3.2015)	Wave – Particle Dualism, Postulates of Quantum Mechanics
Week 3 (19.3.2015)	Magnetic Moment, Time Evolution
Week 4 (26.3.2015)	Bloch Sphere, Rabi Oscillations
Week 5 (2.4.2015)	Operators and Eigenstates
Break	
Week 6 (16.4.2015)	Barriers and Potential Wells
Week 7 (23.4.2015)	Quantum Transport
Week 8 (30.4.2015)	Coulomb Blockade and Single Electron Transistor
Week 9 (7.5.2015)	Assignment 1 (due 5.5.2015, 4pm), Quantum Dots and Quantum Bits
Week 10 (14.5.2015)	Nanofabrication and Cryogenic Techniques (not assessed)
Week 11 (21.5.2015)	Superconductivity and Flux Quantisation
Week 12 (28.5.2015)	Assignment 2 (due 19.5.2015, 4pm), Superconducting Quantum Bits
Week 13 (4.6.2015)	Questions & Answers
TBA	Final Exam

Assessment

Assignment 1	20%
Assignment 2	20%
Final Exam (3 hours)	60%

The final exam will be in written form, and will ask the students to answer questions about concepts, principles, and devices discussed during the course.

The assignment will be based on numerical calculations to predict the dynamics and the properties of some quantum system. The assignments will also have a pedagogical value, in the sense that the students will discover highly non-trivial and intellectually profound results by examining the outcomes of their calculations.

Course Details

Credits

This is a 6 UoC course and the expected workload is 10–12 hours per week throughout the 13 week semester.

Pre-requisites and Relationship to Other Courses

ELEC9705 Quantum Devices is a stand-alone course, with no prerequisites and no following courses.
No previous knowledge of Quantum Mechanics is assumed or expected. However, it is assumed that the students are familiar, conceptually and practically, with:

- Linear algebra (matrix operations, eigenvalues and eigenvectors, etc...);
- Fourier transforms;
- Basic circuit theory;
- Electromagnetism and wave propagation.

Extensive use will be made of Matlab programming, both in simple demonstrations during the lectures, and the mid-term assignments. Matlab can be obtained from UNSW IT via https://www.it.unsw.edu.au/students/software/matlab.html . A free Matlab emulator, such as Octave, may also be used. Octave can obtained via http://wiki.octave.org/Main_Page and a version of Octave for Windows with GUI from http://mxeoctave.osuv.de/ .

Week 1 will be used for a discussion of the aims and scope of the course, a revision of the assumed previous knowledge listed above, plus an introduction to the basics of Matlab use.

The course naturally complements TELE7957 Quantum Communications. The two courses taken together provide a complete pedagogical package on emerging quantum technologies, covering “quantum hardware” (ELEC9705) and “quantum communications” (TELE7957).

Learning outcomes

At the end of the course, the students will:

1. be familiar with the fundamental concepts of Quantum Mechanics, e.g. wave-particle duality, uncertainty principle, Schrödinger’s equation, tunneling, entanglement, etc...;
2. know how to calculate the basic properties (energy spectrum, wave functions, ...) of simple quantum systems;
3. predict the dynamics of a spin or a set of spins;
4. apply the mapping between discrete quantum systems and spins, to describe the dynamics of complex quantum mechanical devices;
5. possess a broad picture of how, why and where quantum effects can appear in engineered nanostructures;
6. be able to recognize the relevance of quantum mechanics for the technological progress in electronic devices, and appreciate the radically new range of device functionality that is made available to the engineer by the control of quantum systems.

This course is designed to provide the above learning outcomes which arise from targeted graduate capabilities listed in ***Appendix A***. The targeted graduate capabilities broadly support the UNSW and Faculty of Engineering graduate capabilities (listed in ***Appendix B***). This course also addresses the Engineers Australia (National Accreditation Body) Stage I competency standard as outlined in ***Appendix C***.

Syllabus

The course on Quantum Devices provides a rigorous but accessible introduction to the working principles and the uncommon properties of nano-engineered electronic devices, whose dynamics no longer obey the laws of classical physics. Such devices are designed to be the building blocks of future quantum information and communication systems, by allowing to observe and manipulate individual electron charges, measure their spin state, and couple them to quantized electromagnetic fields.
The lectures will cover the basics of quantum mechanics, then describe several examples of "quantum bits" based on semiconductors (individual dopant atoms, quantum dots, ...) and superconductors (Cooper-pair boxes, Josephson junctions, ...). Also explained are the quantum point contract, the single-electron transistor and the superconducting quantum interference device, which represent the ultimate detectors of electric and magnetic signals.

Teaching Strategies

Delivery Mode

The lecturer will deliver projected PowerPoint lectures, aided by hand-written slides on the spot or whiteboard sketches. Some use will be made of audio-visual material, like videos, animations and online simulation tools. Lecture notes, additional reading material and, where possible, audio-visuals and web links, will be progressively made available on the course Moodle page, but they are no substitute for accurate notes taken by the students during the lectures. This is because it is probable and desirable that many questions will arise during the lectures, and the outcomes of such discussions are hard to capture in lecture notes prepared in advance. It is, therefore, essential that students attend every lecture. The material covered by the course is rather unusual and it would be difficult for the students to assemble this knowledge by reading scattered references.

Certain concepts will be taught with the aid of Matlab-based numerical calculations, or online simulation tools. The lecturer will introduce the Matlab code and the tools live in the class, and then assign some home exercises to the students. These exercises will play a crucial role in helping the students understanding certain complicated Quantum Mechanical concepts such as “superposition” and “entanglement”.

The numerical exercises developed through live examples and homework will form the background for two assignments, each contributing 20% to the final mark.

There will be no tutorials or laboratories.

Learning in this course

You are expected to attend all lectures, and complete both assignments in order to maximise learning. In addition to the lecture notes/video, you should read relevant sections of the recommended text. Reading additional texts will further enhance your learning experience. Group learning is also encouraged. UNSW *assumes* that self-directed study of this kind is undertaken in addition to attending face-to-face classes throughout the course.

Assessment

The assessment scheme in this course reflects the intention to assess your learning progress through the semester.

Assignment

The assignment allows self-directed study leading to the solution of partly structured problems. Marks will be assigned according to how completely and correctly the problems have been addressed, the quality of the code written for the assignment (must be attached to the report), and the understanding of the course material demonstrated by the report.

The assignment reports will be due on Tuesday 5.5.2015, 4pm in Week 9 and on Tuesday 19.5.2015, 4pm in Week 12, and should be submitted via email to a.laucht@unsw.edu.au . *Late reports will attract a penalty of 10% per day* (including weekends).

Final Exam

The exam in this course is a standard closed-book 3 hour written examination, comprising five compulsory questions. University approved calculators are allowed. The examination tests analytical and critical thinking and general understanding of the course material in a controlled fashion. Questions may be drawn from any aspect of the course, unless specifically indicated otherwise by the lecturer. Marks will be assigned according to the correctness of the responses. *A pass mark for the entire course is achieved when the sum of the marks obtained for the two assignments and the final exam is higher or equal to 50. It is not necessary to obtain a pass in the final exam alone.*

Date and location to be announced.

Course Resources

Textbooks

No textbook is formally set or required for this course.

For the first part of the course, the students might benefit from consulting standard Quantum Mechanics textbooks:

C. Cohen-Tannoudji, B. Diu, F. Laloë, Quantum mechanics, New York: Wiley, 1977;

D. A. B Miller, Quantum Mechanics for scientists and engineers, Cambridge University Press, 2008;

The first is a very extensive treatment of Quantum Mechanics, while the second is a more succinct book, written with an eye to the background and interests of Engineering students.

Further specialized reading material will be made available on the course Moodle website.

On-line resources

Moodle

The Moodle portal will be the primary point of contact, for administrative matters, with the students. Lecture notes, assignments and other course materials will also be made available for download from Moodle.
The students are expected to check regularly the Moodle page for important announcements and practical matters: https://moodle.telt.unsw.edu.au/login/index.php.

Mailing list

Announcements concerning course information will be given in the lectures and/or on Moodle and/or via email (which will be sent to your student email address).

Other Matters

Academic Honesty and Plagiarism

Plagiarism is the unacknowledged use of other people's work, including the copying of assignment works and laboratory results from other students. Plagiarism is considered a form of academic misconduct, and the University has very strict rules that include some severe penalties. For UNSW policies, penalties and information to help you avoid plagiarism, see http://www.lc.unsw.edu.au/plagiarism. To find out if you understand plagiarism correctly, try this short quiz: https://student.unsw.edu.au/plagiarism-quiz.

Students found guilty of academic misconduct, in particular plagiarism - including excessive collaboration, copying another's assignment, or allowing one's assignment to be copied by another student - will not receive any marks for that assignment. In addition, any plagiarism will be referred to the Head of School for further action.

Student Responsibilities and Conduct

Students are expected to be familiar with and adhere to all UNSW policies (see https://my.unsw.edu.au/student/atoz/ABC.html), and particular attention is drawn to the following:

Workload

It is expected that you will spend at least **ten to twelve hours per week** studying a 6 UoC course, from Week 1 until the final assessment, including both face-to-face classes and *independent, self-directed study*. In periods where you need to complete assignments or prepare for examinations, the workload may be greater. Over-commitment has been a common source of failure for many students. You should take the required workload into account when planning how to balance study with employment and other activities.

Attendance

Regular and punctual attendance at all classes is expected. UNSW regulations state that if students attend less than 80% of scheduled classes they may be refused final assessment.

General Conduct and Behaviour

Consideration and respect for the needs of your fellow students and teaching staff is an expectation. Conduct which unduly disrupts or interferes with a class is not acceptable and students may be asked to leave the class.

Work Health and Safety

UNSW policy requires each person to work safely and responsibly, in order to avoid personal injury and to protect the safety of others.

Special Consideration and Supplementary Examinations

You must submit all assignments and attend all examinations scheduled for your course. You should seek assistance early if you suffer illness or misadventure which affects your course progress. All applications for special consideration must be **lodged online through myUNSW within 3 working days of the assessment**, not to course or school staff. For more detail, consult https://my.unsw.edu.au/student/atoz/SpecialConsideration.html.

Continual Course Improvement

This course is under constant revision in order to improve the learning outcomes for all students. Please forward any feedback (positive or negative) on the course to the course convener or via the Course and Teaching Evaluation and Improvement Process. You can also provide feedback to ELSOC who will raise your concerns at student focus group meetings. As a result of previous feedback obtained for this course and in our efforts to provide a rich and meaningful learning experience, we have continued to evaluate and modify our delivery and assessment methods.

Administrative Matters

On issues and procedures regarding such matters as special needs, equity and diversity, occupational health and safety, enrolment, rights, and general expectations of students, please refer to the School and UNSW policies:
http://www.engineering.unsw.edu.au/electrical-engineering/policies-and-procedures
https://my.unsw.edu.au/student/atoz/ABC.html

Appendix A: Targeted Graduate Capabilities

Electrical Engineering and Telecommunications programs are designed to address the following targeted capabilities which were developed by the school in conjunction with the requirements of professional and industry bodies:

- The ability to apply knowledge of basic science and fundamental technologies;
- The skills to communicate effectively, not only with engineers but also with the wider community;
- The capability to undertake challenging analysis and design problems and find optimal solutions;
- Expertise in decomposing a problem into its constituent parts, and in defining the scope of each part;
- A working knowledge of how to locate required information and use information resources to their maximum advantage;
- Proficiency in developing and implementing project plans, investigating alternative solutions, and critically evaluating differing strategies;
- An understanding of the social, cultural and global responsibilities of the professional engineer;
- The ability to work effectively as an individual or in a team;
- An understanding of professional and ethical responsibilities;
- The ability to engage in lifelong independent and reflective learning.

Appendix B: UNSW Graduate Capabilities

The course delivery methods and course content directly or indirectly addresses a number of core UNSW graduate capabilities, as follows:

- Developing scholars who have a deep understanding of their discipline, through lectures and solution of numerical problems in homeworks, and assessed by assignments and written examinations.
- Developing rigorous analysis, critique, and reflection, and ability to apply knowledge and skills to solving problems.
- Developing capable independent and collaborative enquiry, through a series of homeworks and assignments spanning the duration of the course.
- Developing digital and information literacy and lifelong learning skills through assignment work.

Appendix C: Engineers Australia (EA) Professional Engineer Competency Standard

	Program Intended Learning Outcomes	
PE1: Knowledge and Skill Base	PE1.1 Comprehensive, theory-based understanding of underpinning fundamentals	✓
	PE1.2 Conceptual understanding of underpinning maths, analysis, statistics, computing	✓
	PE1.3 In-depth understanding of specialist bodies of knowledge	✓
	PE1.4 Discernment of knowledge development and research directions	✓
	PE1.5 Knowledge of engineering design practice	
	PE1.6 Understanding of scope, principles, norms, accountabilities of sustainable engineering practice	
PE2: Engineering Application Ability	PE2.1 Application of established engineering methods to complex problem solving	✓
	PE2.2 Fluent application of engineering techniques, tools and resources	✓
	PE2.3 Application of systematic engineering synthesis and design processes	
	PE2.4 Application of systematic approaches to the conduct and management of engineering projects	
PE3: Professional and Personal Attributes	PE3.1 Ethical conduct and professional accountability	
	PE3.2 Effective oral and written communication (professional and lay domains)	✓
	PE3.3 Creative, innovative and pro-active demeanour	✓
	PE3.4 Professional use and management of information	✓
	PE3.5 Orderly management of self, and professional conduct	✓
	PE3.6 Effective team membership and team leadership	