SOLA9101
Advanced Photovoltaic Technologies

UNSW AUSTRALIA

Course Outline – Term 1, 2021

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

Course Staff

Course Convener:	A/Prof. Ashraf Uddin, TETB Room 126; a.uddin@unsw.edu.au
Lecturers:	A/Prof. Ashraf Uddin,
Tutors:	Mo Alvin and Londono Daniel

Consultations: For all enquiries about the course please contact the course convener. A regular weekly consultation time is on Wednesday **2 - 4 pm at online (MS Team) or at TETB room 126**. For all other questions or enquiries, you are encouraged to ask the lecturer after class or post your questions on the Discussion Board on Moodle.
https://moodle.telt.unsw.edu.au/login/index.php

Keeping Informed: All course materials and announcements will be posted on Moodle. Please note that you will be deemed to have received this information, so you should take careful note of all announcements.

Course Details

Credits
This is a 6 UoC course and the expected workload is 12–14 hours per week throughout the 10-week semester.

Relationship to Other Courses
SOLA9101 is the level 5 course. It is offered for 3rd and 4th year of UG students and Graduate Diploma and master's Postgraduate programs students in the School of Photovoltaic and Renewable Energy Engineering School. It is a professional elective course for the Photovoltaic and Solar Energy Program. It is a core/elective course for students following a BE (materials science or Electrical Engineering) program and other combined degree programs, and an elective for physics students.

Pre-requisites and Assumed Knowledge
It is assumed that students enrolled in this course are familiar with semiconductor materials and devices such as photovoltaic devices and diodes.

Following Courses
None

Learning outcomes
After successful completion of this course, student should be able to understand:

(1) The physical and electrical properties of semiconductor materials and various photovoltaic device structures.
(2) The working principles of advanced photovoltaic devices such as silicon heterojunction (HIT) cells, multi-junction tandem cells, organic and perovskite solar cells, CIGS, etc.

(3) The performance evaluation and analysis of different advanced solar cells.
(4) Silicon crystal growth and the manufacturing processes of devices such as thermal oxidation, dopant diffusion, physical/chemical vapor deposition, spin-coating, photolithography, and etching processes, etc.

Much of the above experience and knowledge will be gained using lecture notes, tutorials, assignment, and textbooks, self-research, etc.

Syllabus

Semiconductor Materials

The bandgap of semiconductors; band-gap energy, intrinsic and doped semiconductors, carrier transport phenomena, carrier generation and recombination processes, free carrier recombination, free carrier to deep-level recombination, non-radiative recombination.

p-n Junction diodes

Flat-band diagram, thermal equilibrium condition, depletion region, depletion capacitance, current-voltage characteristics, charge storage and transient behavior, junction breakdown, hetero-junction, metal semiconductor ohmic contact.

p-n Junction solar cells

Silicon crystalline solar cells, current-voltage characteristics, Energy conversion efficiency, current flow under illumination, Junction location in solar cells, Effect of doping level in absorber region, Texturing of surface, Surface passivation, Back-surface field, Important solar cell structures.

Silicon heterojunction (HIT) solar cells

Amorphous Si (a-Si) cells, a-Si/c-Si cells, cells structure, energy band diagram of cell structure, working principle of HIT cells, HIT cells performance, stability of cells.

Thin film solar cells

CdTe and CIGS cells, device structures, energy band diagram, working principle of cells, performance of cells, challenging issues of this technology.

Multijunction cells

III-V materials single and multijunction cells, device structures and their energy band diagram, working principle of devices, challenging issues of technology.

Emerging photovoltaic cells

Dye-sensitized cells, perovskite cells, organic cells, inorganic cells (CZTSSe) and quantum dot cells, device structure and their energy band diagram, working principle of cells, device performances, stability of cells.

Bulk Crystal Growth

Crystal structures, Silicon Crystal Growth, Czochralski crystal growth, Silicon crystal doping, defects in wafer. Wafer preparation, Defect treatment: intrinsic/extrinsic gettering.

Diffusion doping and Thermal oxidation
Diffusion equations and profiles; two step diffusion: pre-deposition and drive-in diffusion. Oxidation enhanced diffusion. Thermal oxidation kinetics: Deal Grove equation, linear and parabolic rate coefficients, effects of dopants; Oxide charges; Oxidation equipment: furnace and rapid thermal processor.

Physical Vapor Deposition
Evaporative deposition technique. Principle of sputtering process. Plasma physics of sputtering. Processing considerations: bias, temperature and substrate heating. Structure and properties of sputter deposited films. Sputtering techniques: RF sputtering, DC magnetrons, bias sputtering, reactive sputtering and ion metal plasma sputtering.

Chemical Vapor Deposition
Basic aspects of CVD: gas phase mass transfer/surface reaction, rate determining step, sticking coefficient, step coverage of thin films and advantages/disadvantages. Types of reactions in CVD: APCVD, LPCVD and PECVD.

Spin-coating and ink-jet printing
Deposition of solution materials, Ink-Jet Printing, Microcontact Printing, nanoimprint technology, Self-Aligned Printing,

Photolithography
Basic photoresist technology. Photoresist material parameters: resolution, sensitivity and viscosity. Optical photoresist material types: positive/negative, multilayer and contrast enhancement resists. Photoresist processing: vapor prime, soft bake, alignment, exposure and development. Optics of microlithography. Methods of transferring patterns, pattern registration. Mask and reticle fabrication.

Etching
Wet etching technology, etchants. Lift-off technology for patterning. Basic physics and chemistry of plasma etching and reactive etching: bias, tolerance, anisotropy, selectivity, edge profile and etch rate; dry etching of various thin films.

Contact Hours

Lectures	**Day**	**Time**	**Location**
Lecture	Wednesday	10:00 – 11:00	Online (MS Team)
Lecture	Thursday	12:00 – 14:00	Online (MS Team)
Tutorial	Wednesday	12:00 – 14:00	Online (MS Team) tentative
Tutorial	Wednesday	14:00 – 16:00	Colombo LG01 (face-to-face)
Tutorial	Thursday	9:00 – 11:00	Online (MS Team)

Context and Aims.

This course is designed on photovoltaic devices and processing technology. This course is very important to develop the future workforces for solar cells industry. It is essential for students who desire to specialize in photovoltaic devices including micro- and nanoelectronics. The course covers the basics of the semiconductor materials and advanced photovoltaic devices and processing technology. The major objective is to familiarize the students with the basic principles of operation of all photovoltaic devices such as silicon heterojunction (HIT) cells, multi-junction tandem cells, hot-carrier cells, organic and perovskite solar cells, CIGS, etc... The device processing technology includes: **(i)** crystal structures, silicon crystal growth and Czochralski crystal growth, wafer preparation, defects in wafer, defect treatment, (ii) doping and thermal oxidation of materials, (iii) physical vapor deposition technique, principle of sputtering process, sputtering techniques: RF sputtering, DC magnetrons, bias sputtering, reactive sputtering and ion metal plasma sputtering, (iv) basic aspects of CVD, gas phase mass transfer/surface reaction, rate determining step, sticking coefficient and advantages/disadvantages, types of reactions in CVD: APCVD, LPCVD and PECVD; (v) spin coating, ink-jet printing, micro-contact printing, nanoimprint technology (vi) Photolithography, photoresist material parameters: resolution, sensitivity and viscosity. Optical photoresist material types, photoresist processing, optics of microlithography, methods of transferring patterns, pattern registration, (vi) wet etching technology, etchants, lift-off technology for patterning electrode, basic physics and chemistry of plasma etching and reactive etching, processing issues related to dry etching.

From my industrial experience on semiconductor device process technology as well as on my teaching experience I have prepared the course materials by reviewing many books and articles. This experience will be supported by a series of lectures which present the theory and working principles of solar cell devices. I am always encouraging my students to discuss with me at any time at anywhere if my lecture topics are not clear to them. I am also encouraging my students to discuss on the lecture topics among themselves to make them clear. I will use tutorial problems and assignments from each topic to get in-depth understand on the course. I will take mid-term, term-end exams and final test to press the student to study and understand the course. I will use CATEI reports to improve my course materials and teaching.

Tentative Course Schedule

Week	Lecture	Tutorials
1	Course outlines and Introduction (L1A), Energy bands and carrier conc. (L1B) Carrier transport Phenomena (L1C)	No tutorial (Assignment 1 out)
2	p-n junction diodes (L2A), Silicon solar cells (L2B) Silicon solar cells (L2C)	Tutorial 1
3	Thin film solar cells (L3A) Silicon heterojunction (HIT) solar cells (L3B) Multijunction cells (tandem cells) (L3C)	Tutorial 2
4	Emerging photovoltaic cells (L4A) Emerging photovoltaic cells (L4B) Silicon crystal growth (L4C)	Tutorial 3

5	Mid-session exam (L5A) Silicon crystal growth (L5B) Diffusion and doping of Si (L5C)	Tutorial 4 (Assignment 1 due)
6	Oxidation (L6A) Thermal evaporation (L6B) Sputtering (L6C)	Tutorial 5 (Assignment 2 out)
7	Basic CVD (L7A) Basic CVD (L7B) Spin-coating and ink-jet printing (L7C)	Tutorial 6
8	Lithography (L8A) Lithography (L8B) Etching (L8C)	Tutorial 7
9	Etching (L9A) Lecture Review and Final exam (L9B)	Tutorial 8
10	Exam on self-learning (L10A)	Tutorial 9 (Assignment 2 due)

Assessment

Take-Home Assignment 1&2	20%
Mid-term test	15%
Self-learning exam (Term end test)	15%
Final Exam (2 hours)	50%

- ALL material presented during the session will be examinable in the final exam unless otherwise noted. Final exam papers may have a section devoted to the P-grad research papers/presentations.

- If necessary, the final overall marks will be scaled (possibly separately for U-grads and Pgrads; for Ugrads, it may even be necessary to do this separately for 3rd-year and 4th-year students). [Remark: The average mark for courses in the Faculty of Engineering at UNSW is typically in the 65-72% band.]

- All assessable work (except the final exam) must be submitted with a completed (and signed) cover sheet. The sheet can be downloaded from the SPREE site on Webpage.

- Late assignments will be penalized 5%, plus 5% per day that the work is late (maximum penalty is 100%). Once the solutions are presented, the maximum penalty will apply.

Teaching Strategies

Delivery Mode

The teaching strategy for this course comprises a series of lectures and tutorials problems and classes. The lecture series will present theory related to semiconductor materials and devices and up-to-date information about available equipment, costing, and quality control resources. During tutorials students can also ask tutors any questions they may have about the material taught in lectures.

Lectures: There are 10 weeks lecture online (MS Team) period in semester term T1, 2021. Each week has two lectures in one- and two-hours slots. The lecture time and places are as: Wednesday 10:00 - 11:00, (MS Team) and on Thursday 12:00 – 14:00 at MS Team. All lecture notes will be provided before the lecture, either via UNSW's Moodle site or as photocopied handout.

Tutorials: In the tutorial session student will work in small groups. The tutorial problems will be provided before each tutorial, either via Moodle or as photocopied handout. The solutions will be provided during or after each tutorial class. The tutorial class schedules for Term T1, 2021 is as: Wednesday 12:00 – 14:00 (Online MS Team, tentative), Wednesday 14:00 – 16:00 (Colombo LG01, face-to-face) and Thursday 9:00 – 11:00 (Online, MS Team).

Assignment: There are two assignments in this course. Assignments will be provided via UNSW's Moodle site. The two take-home assignments will be handed out in weeks 1 and 6. Their due dates will be shown on the papers. The solutions may be presented in the tutorial class (but will not be distributed).

Undergraduate and postgraduate students will attend the same lectures and tutorial classes. Students are also strongly encouraged to use the discussion group on Moodle to assist their learning. Tutors will monitor the discussions and help answer posted questions.

Final Exam

Final exam in this course is a standard 2 hour online written examination. 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.

Course Resources

Text and Reference books:

1. S.M. Sze, *Semiconductor Devices (physics and Technology)*, 3rd and 2nd ed. (Wiley, 2012 and 2002).
2. S.M. Sze, "*Physics of Semiconductor Devices*", 3rd Edition (Wiley, 2007); other lecture materials will be drawn from various textbooks and journal papers.
3. M.A. Green, *Solar Cells* (UNSW Bookshop, 1982).
4. Arvind Shah, "Thin-film Silicon solar cells", 2010, CRC press.
5. J. D. Plummer, M. D. Deal and P.B. Griffin, Silicon VLSI Technology, 2000, Prentice Hall.
6. Y. Chang and S.M. Sze, ULSI Technology, 1996, McGraw Hill
7. S. K. Ghandhi, "VLSI Fabrication Principles, 1994, John Wiley.
8. Various Webpages

On-line Resources

- Website: UNSW's Moodle. As a part of the teaching component, Moodle will be used to disseminate teaching materials, host forums and occasionally quizzes. Assessment marks will also be made available via Moodle: https://moodle.telt.unsw.edu.au/login/index.php

- **Lecture Notes:** Lecture notes will be provided before each lecture via UNSW's Moodle site.
- **Tutorials:** Tutorial problems will be provided before each tutorial via moodle. The solutions will be provided after each tutorial class in UNSW moodle site.

- Assignments (and other course materials): will be provided via UNSW's Moodle site.

- **PC1D solar cell simulator:** Is installed on the PCs in TETB. For a personal copy, see www.pv.unsw.edu.au/links/products/pc1d.asp.

- Announcements and Discussion Board: Announcements concerning course information will be given in the lectures and/or on Moodle. A Discussion Board will also be established on the Moodle course page for you to post questions or initiate course-related discussions.

Other Matters:

Academic Honesty and Plagiarism

All assignments and tutorials are for individual effort and individual assessment only. You are expected to be aware of, and you will be subject to, the UNSW and School policies that cover plagiarism of written work (see the PV Undergraduate site on Webpage). Students will be penalised for plagiarism in tutorial, assignment and exam work.

Plagiarism

Plagiarism is the presentation of the thoughts or work of another as one's own. Examples include:[1]

- Direct duplication of the thoughts or work of another, including by copying work, or knowingly permitting it to be copied. This includes copying material, ideas or concepts from a book, article, report, or other written document (whether published or unpublished), composition, artwork, design, drawing, circuitry, computer program or software, web site, Internet, other electronic resource, or another person's assignment without appropriate acknowledgement.
- Paraphrasing another person's work with very minor changes keeping the meaning, form and/or progression of ideas of the original.
- Piecing together sections of the work of others into a new whole;
- Presenting an assessment item as independent work when it has been produced in whole or part in collusion with other people, for example, another student or a tutor; and,

[1] Based on that proposed to the University of Newcastle by the St James Ethics Centre. Used with kind permission from the University of Newcastle.

- Claiming credit for a proportion a work contributed to a group assessment item that is greater than that contributed. [2]

Submitting an assessment item that has already been submitted for academic credit elsewhere may also be considered plagiarism. The inclusion of the thoughts or work of another with attribution appropriate to the academic discipline does *not* amount to plagiarism. Students are reminded of their rights and responsibilities in respect of plagiarism, as set out in the University Undergraduate and Postgraduate Handbooks and are encouraged to seek advice from academic staff whenever necessary to ensure they avoid plagiarism in all its forms.

The Learning Centre website is the central University online resource for staff and student information on plagiarism and academic honesty. It can be located at: https://student.unsw.edu.au/plagiarism. To find out if you understand plagiarism correctly, try this short quiz: https://student.unsw.edu.au/plagiarism-quiz.

The Learning Centre also provides substantial educational written materials, workshops, and tutorials to aid students, for example, in:

- Correct referencing practices.
- Paraphrasing, summarising, essay writing, and time management.
- Appropriate use of and attribution for, a range of materials including text, images, formulae, and concepts.

Individual assistance is available on request from The Learning Centre.

Students are also reminded that careful time management is an important part of study and one of the identified causes of plagiarism is poor time management. Students should allow enough time for research, drafting, and the proper referencing of sources in preparing all assessment items.

Student Responsibilities and Conduct

Students are expected to be familiar with and adhere to all UNSW policies (see https://student.unsw.edu.au/guide), 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 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

Responsibility for earning marks rests solely with the student. Thus, it would be a smart thing to attend lectures, to avail yourself of the subject resources (as above), to complete your assignments on time and to the best of your ability, participate in the tutes, and to be fully aware of the course syllabus, including any announcements or changes to that syllabus.

[2] Adapted with kind permission from the University of Melbourne.

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. Students are expected to not distract their colleagues during lectures and tutorials.

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://student.unsw.edu.au/special-consideration.

Continual Course Improvement

At the end of the course, students will be asked to complete two evaluation forms – one for the course and one for the course coordinator using the UNSW's Course and Academic Teaching Evaluation and Improvement (CATEI) Process. Your feedback is much appreciated and taken very seriously. Continual improvements are made to the course based in part on such feedback and this helps us to improve the course for future students.

This course is under constant revision 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 RESOC 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: UNSW Graduate Capabilities

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

- Developing scholars who have a deep understanding of their discipline, through lectures and solution of analytical problems in tutorials and assessed by assignments and written examinations.

- Developing rigorous analysis, critique, and reflection, and ability to apply knowledge and skills to solving problems. These will be achieved by the tutorial problem solving as well as assignments.
- Developing ethical practitioners who are collaborative and effective team workers, through group activities, seminars, and tutorials.
- Developing independent, self-directed professionals who are enterprising, innovative, creative, and responsive to change, through challenging design and project tasks.
- Developing citizens, who can apply their discipline in other contexts, are culturally aware and environmentally responsible, through interdisciplinary tasks, seminars, and group activities.

Appendix B: 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	✓