EECS 517 (NERS 578). Physical Processes in Plasmas
Fall 2010 - TuTh 10:30 AM - 12:00 PM - 1012 EECS

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Grader-Teaching Assistant: To be announced

Goals of Course: This course addresses the fundamental science and the technology of low temperature, partially ionized, non-equilibrium plasmas. This class of plasmas is used, for example, for etching and deposition of materials, surface treatment, lighting sources, flat panel displays, welding, laser ablation, lasers and biomedical applications. These plasmas are also naturally occurring, such as the aurora, shock waves and lightning. The objectives of this course are to first provide a foundation of the fundamentals of electron-atom collisions, electron and ion transport and the different ways in which low temperature plasmas are created. After providing this foundation, the course will apply those fundamentals to study of technologies which use partially ionized plasmas, with examples taken from lasers, plasma materials processing, lighting sources and plasma medicine.

Grading Policy: The field of low temperature plasmas is intrinsically interdisciplinary. The linkages between the supporting fields are best appreciated by problem solving in a real-world context. As a result, one will not be able to fully benefit from the course without putting a good-faith effort into the homeworks. To acknowledge the importance of homework, it is being heavily weighted in the grading policy. The grading policy will be:

Homework	30%
Mid-Term Exam	30%
Final Project	30%
Instructor's discretion	10%

Instructor's discretion includes my qualitative assessment of students' effort towards the course (e.g., class attendance and participation).

Texts:

Required: M. Lieberman, Principles of Plasma Discharges and Material Processing, 2nd Edition (Wiley, New Jersey, 2005)

Optional Text: A. Friedman and L. A. Kennedy, Plasma Physics and Engineering (Taylor and Francis, New York, 2004)

Note that both of these texts are available electronically through a subscription by the UM Engineering Library.

"Principles of plasma discharges and materials processing" can be accessed online at http://proxy.lib.umich.edu/login?url=http://www.myilibrary.com?id=25507

"Plasma physics and engineering" can be accessed online at http://proxy.lib.umich.edu/login?url=http://www.myilibrary.com?id=34790

Course Website: The course website will be located at "http://uigelz.eecs.umich.edu → Classes → EECS 517 ". The materials that will be posted on the website include:

1. Introductory materials
2. Homework assignments
3. Handout Packages (Note that some, but NOT ALL of the handouts can also be downloaded individually!)
4. Class announcements (such as cancellations, rescheduled classes, exam dates)

Course Map

"Gaseous Electronics is the study partially ionized gases and their application to technologically relevant devices."

MICROSCOPIC → MACROSCOPIC

Electron collisions

Cross sections, rate coefficients

Gas discharge theory
Electron production, loss
Sheaths
Electron distribution functions
Transport coefficients

Low pressure dc discharge devices

High pressure discharges and
e-beam pumped plasmas

rf and microwave discharges

Diagnostics

Applications:
Plasma etching
Toxic Gas Remediation
Special Topics

Syllabus and Reading Assignments (Version 01)

Reading assignments in Lieberman are required. Others are recommendations for background.

Unit	Topic	Reading Assignments (Chapters or sections)	
		Lieberman	Fridman
I.	Introduction	1	1
II.	Electron Collisions	3,8 Appendix A	2,3
III.	Cross Sections and Rate Coefficients	3,8	2,3
IV.	Gas Discharges	2	7
V.	Electron Continuity Equation, Diffusion, Production, Loss	2,5	4.5
VI.	Sheaths	6.1-6.5 Handouts	6.1
VII.	Electron Distribution Functions	2, Appendix B	4.1-4.2
VIII.	Transport Coefficients	5	6
IX.	Low Pressure DC Discharges	10,14	7.12-7.8
X.	High Pressure Discharges and Electron Beam Pumped Plasmas	Handouts	12
XI.	RF and Microwave Discharges	11,12	10.5-10.6, 10.9
XII.	Fully Ionized Plasmas	4, Handouts	
XIII.	Magnetic Fields in Discharges	4	6.2
XIV.	Inductively Coupled Plasmas	12	10.7
XV.	Diagnostics	6.6	
XVI.	Applications and Special Topics (to be selected by class)		
	a. Plasma Etching/Deposition/Surface Chemistry	7 , 9, 15, 16	
	b. ECR and Helicon	13.1,13.2	10.8
	c. Plasmas in Liquids	Handouts	
	d. Plasma Medicine	Handouts	
	e. Dielectric Barrier Discharges	Handouts	

Required:	M. Lieberman, Principles of Plasma Discharges and Material Processing, 2nd Edition (Wiley, New Jersey, 2005)
Optional Text:	A. Friedman and L. A. Kennedy, Plasma Physics and Engineering (Taylor and Francis, New York, 2004)

Class Schedule (Version 02)

The class schedule is listed below. Due to my travel commitments this Fall, we have scheduled alternate makeup lectures on Friday afternoons. The times and locations of the alternate classes are:

Alternate Classes:

Date		Time	Room
17	Sept.	4:00 – 5:30 pm	DOW 1018
24	Sept.	4:00 – 5:30 pm	DOW 1018
1	Oct.	4:00 – 5:30 pm	DOW 1018
15	Oct.	4:00 – 5:30 pm	EECS 1012
29	Oct.	4:00 – 5:30 pm	EECS 1012
5	Nov.	4:00 – 5:30 pm	EECS 1012

Class Schedule:

Class	Day	Date		Comment	Approximate (!) Topic (See Syllabus for Reading Assignment)
1	T	7	Sept.		Introduction
2	Th	9	Sept.		Electron Collisions
3	T	14	Sept.		Electron Collisions
4	Th	16	Sept.		Cross Sections and Rate Coefficients
5	F	17	Sept.	Alternate Class	Cross Sections and Rate Coefficients
	T	21	Sept.	MJK Travel	
	Th	23	Sept.	MJK Travel	
6	F	24	Sept.	Alternate Class	Gas Discharges
7	T	28	Sept.		Electron Continuity, Diffusion, Sources
	Th	30	Sept.	MJK Travel	
8	F	1	Oct.	Alternate Class	Electron Continuity, Diffusion, Sources
	T	5	Oct.	MJK Travel	
	Th	7	Oct.	MJK Travel	
9	T	12	Oct.		Electron Continuity, Diffusion, Sources
10	Th	14	Oct.		Sheaths
11	F	15	Oct.	Alternate Class	Electron Energy Distributions
	T	19	Oct.	Fall Study Break	
	Th	21	Oct.	MJK Travel	
12	T	26	Oct.		Electron Energy Distributions
13	Th	28	Oct.		Transport Coefficients
14	F	29	Oct.	Alternate Class	Low Pressure DC Discharges
15	T	2	Nov.		Low Pressure DC Discharges
16	Th	4	Nov.		High Pressure and e-beam pumped plasmas
17	F	5	Nov.	Alternate Class	High Pressure and e-beam pumped plasmas
18	T	9	Nov.		RF Discharges
19	Th	11	Nov.		RF Discharges

20	T	16	Nov.		Fully Ionized Plasmas
21	Th	18	Nov.		Magnetic Fields in Discharges
22	T	23	Nov.		Magnetic Fields in Discharges
	Th	25	Nov.	Thanksgiving Recess	
23	T	30	Nov.		Inductively Coupled Plasmas
24	Th	2	Dec.		Diagnostics
25	T	7	Dec.		Special Topics – or Project Presentations
26	Th	9	Dec.		Special Topics – or Project Presentations
	M	13	Dec.	Final Project Due (5:00 pm)	

Supplementary Texts and References
**= On Reserve at UM Engineering Library

J. R. Roth **Industrial Plasma Engineering. Vol 1 & 2** **
Practical view of low temperature plasma physics from
an engineering perspective.

A. Fridman and L. A. Kennedy **Plasma Physics and Engineering** **
Comprehensive text on low temperature plasmas

A. Fridman **Plasma Chemistry** **
Physics of low temperature plasmas and application to gas
phase and surface chemistry.

*C. K. Birdsall and A. B. Langdo*n **Plasma Physics via Computer Simulation** **
Introductory text on the use of Particle-in-Cell simulations
for modeling plasmas.

M. Mitchner **Partially Ionized Gases** **
Mostly for fully ionized plasmas but good treatment of sheaths,
continuity equations, and electron-ion collisions.

G. Bekefi **Principles of Laser Plasmas**
Specialty items such as recombination, discharge stability and
vibrational excitation.

L. M. Biberman, et al. **Kinetics of Nonequilibrium Low-Temperature Plasmas**
Good general reference but difficult to read.
(Russian Translation)

S. C. Brown **Basic Data of Plasma Physics**
Classic text for most topics.

B. Chapman **Glow Discharge Processes**
Good “gut level” monograph. Good source for RF discharges.

F. F. Chen **Introduction to Plasma Physics**
Fully ionized plasmas with good treatment of Debye lengths, and
magnetic field effects.

B. Cherrington **Gaseous Electronics and Gas Lasers**
Good basic introduction.

J. Cobine **Gaseous Conductors**
Extremely empirical treatment of topics but good presentation.
(You can learn something from this book on the first reading.)

L. Huxley **Diffusion and Drift of Electrons in Gases**
Advanced monograph on Boltzmann Equation and Transport Coefficients.

U. Kortshagen **Electron Kinetics and Applications of Glow Discharges**
Proceedings of NATO Workshop. Very good overview articles

L. Loeb **Basic Processes of Gaseous Electronics**
Classic and comprehensive text.

D. Manos and *D. Flamm* **Plasma Etching: An Introduction**
Compilation on methods in plasma processing.

T. Mark **Electron Impact Ionization**
Thorough treatment of electron impact collisions producing ionization

E. McDaniel **Ion Molecule Reactions**
Advanced monograph on reactions between ions and neutral atoms/molecules. Good tables of reaction rate coefficients.

L. C. Pitchford, et al. **Swarm Studies and Inelastic Electron-Molecule Collisions**
Compilation of papers on fundamental studies in nonequilibrium electron transport and obtaining cross sections from swarm data.

Y. Razier **Gas Discharge Physics**
If you are going to buy a second text, get this one. It has all the material that's important, but is difficult to read.

Y. Razier **Radio Frequency Capacitive Discharges**
Exhaustive treatment of this important discharge device for plasma etching.

S. Rossnagel **Handbook of Plasma Processing Technology**
Compilation of papers on basics of plasma etching and deposition.

B. M. Smirnov **Physics of Ionized Gases**
Good general reference but difficult to read.
(Russian Translation)

A. von Engel **Ionized Gases**
Collection of lectures given at Oxford.
Considered a classic for introduction to field.

A. von Engel **Electric Plasmas; Their Nature and Uses**
Simplified view of gas discharges but good introduction.

J. Waymouth **Electric Discharge Lamps**
Defining text for fluorescent lamp physics.

Projects

In lieu of a final exam, there will be a final project. The project should consist of developing a model for, or performing an in depth analysis of, a low temperature plasma or electric discharge system. Some possible choices of electric discharge systems are:

- Plasma processing reactors
- Fluorescent lamps
- He-Ne, excimer, CO_2 lasers
- Sputter deposition reactors
- E-beam pumped systems
- Arc jets and plasma thrusters

The project should include a literature search to provide you with background on how these devices operate and to see how other researchers have analyzed them. Some of the models which appear in the literature are quite involved and complex. The intent of the project is not for you to duplicate the complexity of those models. Rather, the intent is to give you some sense of how the device and the "final product" (e.g., laser power, deposition rate, etch rate) scales. Your model should have at least the degree of sophistication of our homework assignments but should include real device parameters. For example, use the actual gas pressures, gas mixtures, dimensions, cross sections, currents, and voltages. (Note, you can obtain the real cross sections for the majority of cases of interest by request from M. Kushner.)

Your final project deliverables will consist of the written report and, optionally, a presentation to the class. The limit on length is 25 pages, though 25 pages are not required. (Fewer pages of higher quality are preferred.) Please include a description of the discharge system, how you have analyzed it, the scaling laws you developed and a discussion of what you have learned. Generously use plots to display parametric results. Your analysis might include issues such as:

- Electron densities
- Electron and ion temperatures
- Current density, power deposition, operating E/N
- Etch or deposition rates
- Electron or ion energy distributions
- Efficiency of producing the "product"
- Densities of excited states.
- Spectrum of emitted light.

Due dates: Optional Oral presentations: December 7 & 9, 2010
Report: Monday, December 13, 2009, 5:00 PM
Paper copy to Prof. Kushner office, PDF copy to
mjkush@umich.edu

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Units and Best Practice

Units prove to be a confusing aspect of this course. The units which are *commonly in use* in the field are the "standard" for this course. Unfortunately, the units are "mixed" (that is, a mixture of cgs and mks). Some useful conversion factors are listed below. Some best practices you should follow are:

1. ALWAYS perform a units analysis and perform a "sanity" check to determine that your answer is reasonable. In most cases, "unreasonable" answers are a result of unit problems. For example, if your answer is that the argon ion density in a plasma etching reactor is 10^{50} ions/cm^3, your answer is unreasonable and you probably have a units problem. You know your answer is unreasonable since if the density is really 10^{50} argon ions/cm^3, the mass of 10 cm^3 of the plasma would be equal to twice the mass of the earth.

2. **Never, ever be confused by expressing temperature in Energy Units (or vice-versa). Temperature in Energy Units ALWAYS Means**

$$T\ (\mathrm{eV}) \equiv kT\ (\mathrm{eV})$$

3. Unless specified otherwise, you final answers in homework problems should be expressed in the following units.

Electron energies or temperatures	eV
Atomic or molecular energies or temperatures	K or eV
Lengths	cm
Electron, atomic or molecular masses	AMU or g
Electron, atomic or molecular speeds	cm/s
Cross sections	cm^2 or A^2
Mobilities	cm^2/V-s
Diffusion coefficients	cm^2/s
Rates coefficients (1st, 2nd, 3rd order)	s^{-1}, cm^3/s, cm^6/s
Electric fields	V-cm^{-1}
Normalized Electric Fields	V-cm^{-2} or Td (10^{-17} V-cm^2)
Densities	cm^{-3}
Power	W
Power deposition (specific)	W-cm^{-3}
Current density	Amps-cm^{-2}

Useful Conversion Factors

$k = 1.38 \times 10^{-16}$ erg/K = 1.38×10^{-23} J/K

1 eV = 1.6×10^{-12} ergs = 1.6×10^{-19} J ≡ 11,594.2 K

$q = e = 1.6 \times 10^{-19}$ C (coulomb) = 4.8×10^{-10} esu

1 V = 1 J/C = 10^7 erg/C

$\varepsilon_o = 8.85 \times 10^{-12}$ [F/m or C^2/m-J] = 8.85×10^{-14} [F/cm or C^2/cm-J]

m_e (electron mass) = 0.911×10^{-27} g = 0.911×10^{-30} kg

E/N: 1 Td (Townsend) = 10^{-17} V-cm^2 = 10^{-21} V-m^2 = 0.354 V/cm-Torr at (T = 273 K)

1 Å^2 = 10^{-16} cm^2 = 10^{-20} m^2

1 atm = 760 Torr = 1.013 bar

Gas Density: $N = \dfrac{P}{kT} = 9.654 \times 10^{18} \dfrac{P(\text{Torr})}{T(\text{K})}$ cm^{-3}

1 m^3 = 10^6 cm^3

Useful Relationships

Electron speed for energy ε : $v = \left(\frac{2\varepsilon}{m_e}\right)^{1/2}$ = 5.93 x 10^7 $(\varepsilon(\text{eV}))^{1/2}$ cm/s

Average electron thermal speed for temperature T_e: $v = \left(\frac{8kT_e}{\pi m_e}\right)^{1/2}$ = 6.69 x 10^7 $(T_e(\text{eV}))^{1/2}$ cm/s

Debye Length: $\lambda_D = \left(\frac{\varepsilon_o kT_e}{n_e q^2}\right)^{1/2} = \left(\frac{kT_e}{4\pi n_e q^2}\right)^{1/2} = 743\left[\frac{T_e(eV)}{n_e\left(cm^{-3}\right)}\right]^{1/2} cm$

mks cgs

Plasma Frequency:

ω_p (radian/s) $= \left(\frac{n_e q^2}{m_e \varepsilon_o}\right)^{1/2} = \left(\frac{4\pi n_e q^2}{m_e}\right)^{1/2} = 5.64\times10^4\left[n_e\left(cm^{-3}\right)\right]^{1/2}\frac{radians}{s}$

mks cgs

Rate coefficient: $k\left(\frac{cm^3}{s}\right) = \langle \sigma \bullet v \rangle$ (e.g. (e.g. $\frac{\partial N}{\partial t} = n_e kN$))

σ = cross section cm^2 v = velocity cm/s

Conductivity: $\sigma = \frac{n_e q^2}{m_e \nu_m} = 2.81\times10^{-4}\frac{n_e\left(cm^{-3}\right)}{\nu_m\left(s^{-1}\right)}\frac{1}{\Omega - cm}$

ν_m = electron momentum transfer collision frequency

Electron Mobility: $\mu_e = \frac{q}{m_e \nu_m} = \frac{1.756\times10^{15}}{\nu_m\left(s^{-1}\right)}\frac{cm^2}{V - s}$