Fundamentals of Semiconductor Physics

万 歆

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In memory of Prof. Xie Xide (1921-2000)
Syllabus

• Introduction – 3 hours
• Semiconductor physics – 6 hours
  a) bond/band  b) impurities/defects  c) statistics  d) transport
• Silicon technology – 3 hours
• Junctions and contacts – 6 hours
  a) p-n junction  b) heterojunction  c) metal-semiconductor contact
• MOS (metal-oxide-semiconductor) – 6 hours
• Low-dimensional physics – 15 hours
  a) two-dimensional electron gas  b) integer quantum Hall effects
  c) fractional quantum Hall effect and topological quantum computation
• Student presentation on graphene – 9 hours
What I hope you understand are

• what motivate us to do fundamental research,
• how one can apply basic principles of quantum mechanics, statistical mechanics, and solid state physics to real life,
• how fundamental research and applications can influence each other, and
• some research frontiers (hopefully) related to future industry of electronics.

• Do not pay attention to what I say, pay attention to what I mean!
References

S.M. Sze

Muller/Kamins

Yu/Cardona
Solid State Physics Books

Ashcroft & Mermin

Kittel
Motivation

• Rapid development in semiconductor industry
  – Requires fundamental understanding of semiconductor physics
    e.g., transistors, MOSFET, …
  – Motivates fundamental physics problems
    e.g., disordered physics, interacting physics, …
  – Leads to innovated samples and techniques for experiments
    e.g., two-dimensional electron gases, quantum wires, dots, …

• Story: The rise and fall of Bell Laboratories
Ten Bell Labs innovations that changed the world:

- **Data Networking**: fax machine (1925); computer remote operation; DSL.
- **The Transistor** (1947).
- **Cellular Telephone Technology**: first proposal of a cellular network (1947).
- **Solar Cells**: first practical device (1954).
- **Laser**: scientific paper (1958).
- **Digital Transmission and Switching** (1962).
- **Communications Satellites** (1962).
- **Touch-Tone Telephone** (1963).
- **Digital Signal Processor, or DSP** (1979).
Nobel Prizes in Physics

Bell Labs staff have won/shared the Nobel Prize for Physics no less than 8 times:

1937: Clinton Davisson, for his demonstration of the wave nature of matter.

1956: John Bardeen, Walter Brattain and William Shockley, for the invention of the transistor.

1964: Charles Townes, for his work in quantum electronics that led to the invention of lasers.

1977: Philip Anderson, for studies on the electronic structure of magnetic and disorder materials, particularly his examinations of electricity flow through glassy and crystalline materials.

1978: Arno Penzias and Robert Wilson, for their detection of cosmic background radiation, the still reverberating echoes of the Big Bang.

1996: Douglas Osheroff, for the discovery of superfluidity in helium-3.

1997: Steven Chu, for the development of a laser method to cool atoms.

1998: Horst Stormer and Dan Tsui for their discovery of fractional quantum Hall effect, and Bob Laughlin, for his theory of the novel quantum liquid.
The birth of transistor

William Bradford Shockley
John Bardeen
Walter Houser Brattain

Nobel Prize in Physics 1956
Semiconductor research leading to the point contact transistor

“It is interesting to note that although Brattain and Pearson had had considerable experience in the field prior to the war, none of us had worked on semiconductors during the war years. We were able to take advantage of the important advances made in that period in connection with the development of silicon and germanium detectors and at the same time have a fresh look at the problems….

The general aim of the program was to obtain as complete an understanding as possible of semiconductor phenomena, not in empirical terms, but on the basis of atomic theory. A sound theoretical foundation was available from work done during the thirties….”

-- John Bardeen, Nobel Lecture, Dec. 11, 1956
“The objective of producing useful devices has strongly influenced the choice of the research projects with which I have been associated. It is frequently said that having a more-or-less specific practical goal in mind will degrade the quality of research. I do not believe that this is necessarily the case and to make my point in this lecture I have chosen my examples of the new physics of semiconductors from research projects which were very definitely motivated by practical considerations.”

-- William Shockley, Nobel Lecture, Dec. 11, 1956
“My decision to come to Bell Telephone Laboratories immediately after obtaining my Ph.D. in 1936 was strongly influenced by the fact that my supervisor would be C. J. Davisson. Upon my arrival I was assigned by Dr. M. J. Kelly to an indoctrination program in vacuum tubes. In the course of this program Dr. Kelly spoke to me of his ideal of doing all telephone switching electronically instead of with metal contacts. Although I did not choose to continue work on vacuum tubes and was given freedom to pursue basic research problems in solid-state physics, Dr. Kelly’s discussion left me continually alert for possible applications of solid-state effects in telephone switching problems. Insofar as my contribution to transistor electronics has hastened the day of a fully electronic telephone exchange, it was strongly stimulated by the experiences given me during my early years at the Laboratories.”
Eventually Bell’s success ended too. After years of litigation, AT&T spun off its regional telephone service as seven separate companies in 1984, ending the decades of cosy monopoly. A dozen years later, it spun off most of Bell Labs along with its equipment division as Lucent Technologies, which initially prospered but then stumbled badly, shrinking from a peak of 160,000 employees to 30,500 before merging with Alcatel ... It will be missed - it already is. The greatest loss is not so much Bell’s vaunted basic research, but its unique ability to marshal teams of top technologists to transform bright ideas into effective technology.
Bell Labs may be gone, but its innovations are everywhere.
What, then, was the key to its success?

A large part of it was the way it encouraged its employees to strive for great ideas and tackle the toughest problems. The company trained technical managers to inspire staff, with ideas rather than meddle with details, and could afford to have multiple teams try different approaches at once. No doubt it also benefited from the security of working for a regulated monopoly insulated from the whims of the marketplace.

-- “Bell Labs: Over and out”, 《 New Scientist 》
The best science and technology result from bringing together and nurturing the best minds.

-- Frank B. Jewett
Airline branches with an additional branch

Mathematician came to the rescue

2 > $\sqrt{3}$!
The Nobel Prize in Physics 1998

"for their discovery of a new form of quantum fluid with fractionally charged excitations."

Robert B. Laughlin
Stanford University

Daniel C. Tsui
Princeton University

Horst L. Störmer
Columbia University
Laughlin’s theory pointed out that at low temperature and under high magnetic field electron gas condenses into a new kind of quantum fluid. Normally, electrons do not like to condense; they are fermions. They have to combine with magnetic flux quanta before they can condense. Specially in Tsui and Stormer’s discovery, each electron captures three flux quanta, forming a composite particle (boson), which can condense.