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Ex. 2, p. 158, orally

a) What did the development of efficient blue LEDs require?
   It required the production of GaN-based alloys with different compositions and their integration into multilayer structures such as heterojunctions and quantum wells.
b) What technologies are used in today's high-efficiency white electroluminescent light sources?
   Two different technologies are used. The first is to direct blue light through phosphor, which excites and emits red and green lights that combine with the original blue light to create what we see as white. And the second is to use separate LEDs for three complementary colors (e.g. red, green, and blue).
c) Why does the use of efficient blue LEDs lead to significant energy savings?
   It does because efficient blue LEDs use ten times less energy then conventional light bulbs, and lighting accounts for about 20–30% of our total energy consumption.
d) Whose theoretical developments took place prior to the formulation of the modern theory of electronic structure of solid-state materials?
   Theoretical developments of H. J. Round and O. Losev did it.
e) Who realized that a p-n junction could be an interesting device for light emission?
   Kurt Lehovec and co-workers of the Signal Corps Engineering Laboratory in the USA realized it.
f) Why was GaAs attractive in developing techniques to make efficient p-n junctions?
   GaAs was attractive because of its direct band gap, which enables recombination of electrons and holes without involvement of phonons.
g) Why is it important that the semiconductors have direct band gaps?
   Such semiconductors are much more efficient because ones with indirect band gaps require phonon-assisted recombination.
h) What is the quantum efficiency of an LED?
   It is the ratio of the number of emitted photons to the number of electrons passing through the contact in a given time.
i) Which research groups made progress in making efficient LEDs using GaP at the end of the 1950s and what experiments did they conduct?
   There were three groups: Philips Central Laboratory in Germany, Services Electronics Laboratories in the UK, and Belle Telephone Laboratories in the USA. They used different dopants at various concentrations to generate wavelengths from red to green.
j) What are the basic properties of gallium nitride?

GaN is a semiconductor of the III-V class, with Wurtzite crystal structure. It can be grown on a substrate of sapphire (Al2O3) or SiC, despite the difference in lattice constants. GaN can be doped, e.g. with silicon to n-type and with magnesium to p-type. But doping interferes with the growth process so that the GaN becomes fragile. In general, defects in GaN crystals lead to good electron conductivity, i.e. the material is naturally of n-type. GaN has a direct band gap of 3.4 eV, corresponding to a wavelength in the ultraviolet.

k) What research did Philips Research Laboratories carry out using gallium nitride?
   They were developing a new lighting technology and obtained efficient photoluminescence from GaN over a wide spectral range.

l) What new crystal growth technique did Shuji Nakamura develop?
   He developed a technique for growing GaN crystals, in which a thin layer of GaN is first grown on a substrate of sapphire at low temperature and then heated to grow the rest of the crystal.

m) What important observation did Amano, Akasaki and their colleagues make in connection with the doping of GaN?
   They noted that when Zn-doped GaN was studied with a scanning electron microscope, it emitted more light, thus indicating better p-doping. It was a breakthrough in p-n-junction development.

n) Which alloys are necessary in order to produce heterojunctions?
   The necessary alloys are AlGaN and InGaN.

o) What combinations did Nakamura exploit for producing heterojunctions and quantum wells?
   He exploited the combinations InGaN/GaN and InGaN/AlGaN.

p) What are the basic applications of LEDs?
   LEDs are very efficient for lighting. They are also used for liquid crystal displays. UV-emitting diodes are used in DVDs and may be used for water purification in the future.