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Theory and Operation Of Semiconductor Lasers

Abstract

The theory and practical implementation of laser diodes is investigated. The technical focus is on the properties of semiconductors and the technologies that have advanced the capabilities of laser diodes. Specific attention is paid to double heterostructure diode laser and double heterostructure quantum well diode laser.

Motivation

Diode lasers have found use in many different applications and thus their development has had many sources of funding. Advances in the capabilities of diode lasers have in turned spurred the development and creation of more new applications for diode lasers in turn creating new investment in the diode laser. The communications industry has led the way in advancing the capabilities of diode lasers, but others applications in medicine, data storage, atomic physics, and printing technology have also contributed ([5], 3).

Fiber optic technology has become the backbone of the communications industry for transmitting immense quantities of data at high speeds. The total internal reflection (TIR) property of fiber optics is not itself enough to make fiber a good data transmission medium. Efficient data encoding and long range transmission in optical light requires a powerful and coherent light source capable of modulation ([1], 294). Lasers meet these requirements from their very nature, but diode lasers provide even more advantages. Diode laser operation is much more efficient in converting electrical to optical energy than other forms of lasers, and they are extremely compact. Furthermore, developments in material science have made diode laser operation extremely reliable under many conditions including ocean floors where replacement is expensive.

Development And Operating Principles

Diode lasers achieve the lasing threshold in a Fabry-Pérot like container like other types of lasers. On a semiconductor, the mirrors that form the Fabry-Pérot are called facets. The main feature that distinguishes laser diodes from other types of lasers is the direct injection of charge carriers into the excited state inside the active material. The active material is the location in the diode responsible for the creation and amplification of light. N.G. Basov received the nobel prize for first suggesting the use of a semiconductor substrate in 1961 to build a laser operated by direct charge injection. Unlike the atoms in gas or solid state laser types, electrons in laser diodes occupy energy levels that are arranged in groups called bands separated by regions forbidden to electrons called band gaps ([9], 7). The key realization was that, given the right choice of semiconductor material with appropriately spaced bands, electrons injected into higher energy bands could fall into empty positions in lower bands with a change in energy equal to the energy of optical light. The bands of the semiconductors would then be used to maintain the population inversion that is normally held between energy levels in discrete atoms for other types of lasers.

The first laser diodes used a single material, gallium arsenide (GaAs), doped to form a single p-n junction. The experimenters observed a spectral line at Energy 1.47eV, corresponding to 843nm light, which is in the near infrared [8].

$$E = \hbar \omega_{cv} \qquad \lambda = \frac{2\pi c}{\omega} \tag{1,2}$$

The energy corresponding to that wavelength is important in understanding the relation between the structure of the semiconductor and its ability to emit visible light. The 1.47eV is the energy difference between the conduction and valence bands in the bulk material. This is indicated by the *cv* subscript on the angular frequency variable *ω* in (1).

The first semiconductor lasers shared many of the same problems as the first solid state ruby laser did. The homostructure GaAs lasers operate only in very short pulses and only at cryogenic temperatures because the lasing threshold isn't reached until there is a current density of 10 to 100 kilo-Amps per square centimeter. Despite these shortcomings, the homostructure is a useful device for explaining the basic principles of semiconductor bandgaps and their use in creating coherent light ([9], 36).

Semiconductor materials have two different types of bandgaps. Semiconductors in the IV column of the periodic table have indirect transition type, whereas semiconductors made from II-VI and III-V usually have direct transition type. Electrons in the semiconductor can be represented by a Bloch Function.

$$\left|\psi_k(\vec{r})\right\rangle = \left|e^{i\vec{k}\cdot\vec{r}} u_k(\vec{r})\right\rangle \tag{3}$$

Here $u_k(\vec{r})$ represents the periodicity of the crystal structure of the semiconductor and $\vec{k}$ is the wave vector of the electron. When the wave vector of the conduction band and the valence band where the electron is moving between are the same then momentum is conserved ([11], 31). If the electron hole pair must change its wave vector in the transition then in order to conserve momentum the crystal lattice will compensate for the change with a phonon (See Figure 1). Vibrations in the crystal lattice alter the properties of the material causing changes to the index of refraction and heating the system or even scattering the charge carriers. These reasons make indirect transition type semiconductor materials unsuitable for laser purposes.

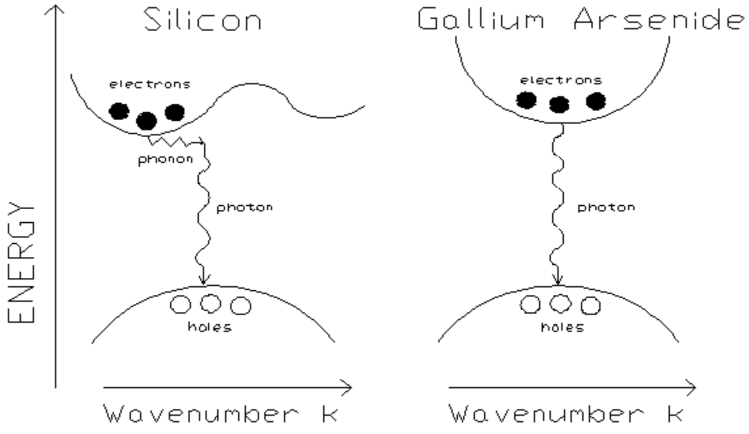

Figure 1: Difference between band transition types. Indirect transition left. Direct transition right.

The GaAs homostructure is actually in two parts that meet at a p-n junction. Pure GaAs has a filled valence band and an empty conduction band, which is not suited for creating population inversion. Impurities are mixed into the crystal lattice to obtain the extra charge carriers necessary to create the conditions for charge carrier movement. Impurities of a type that accept electrons, p – acceptor impurities, are put into one GaAs crystal, and impurities that donate electrons, n – donor impurities, are put in another GaAs crystal. When these two are brought together they form a p-n junction. The valence band of the p-doped material has holes in it and the conduction band of the n-doped material has electrons in it. These are called carriers. As long as the fermi-energy sits inside the bandgap and the thermal energy, $k_b T$, is low then the carriers don't have enough potential energy to cross the gap without an applied voltage. The Fermi-Dirac function describes the distribution of the energy states of carriers in a material with the Fermi level *F* and at temperature *K*.

$$f(E) = \frac{1}{1+e^{(E-F)/k_B T}} \tag{4}$$

Then by applying a voltage across the junction, one injects current through the n-doped region so that the electron energies in the n-doped conduction band reach the energy level of the empty p-doped conduction band. Once the carriers reach that level of energy, holes will move into the valence band and electrons into the conduction band of the p-doped material. Thus the necessary population inversion is reached because there are more electrons in the higher energy state. Spontaneous and more importantly stimulated emission follow by the recombination of holes and electrons, and lasing is achieved.

The minimum required energy of the injected electrons is the same as the energy in equation (1). This time in terms of the applied voltage:

$$E > \hbar\omega_{cv} = eV \tag{5}$$

Now the energy relationship between the emitted light and the electrons has been connected to the energy spacing between the conduction and valence bands as well as the structure of p-n junctions. From this it should be clear that the electron energy is being directly transferred to photon energy and that the quantum efficiency of such a system is very high.

Understanding where the problems of the homostructure laser come from can now be explained easily. The p-doped region is a uniform volume so the charge carriers that are needed to form the population inversion may diffuse out into that volume thus lowering the population inversion density and the optical gain. The surrounding p and n substrates also have a mostly uniform index of refraction so the light generated in the active region around the junction easily spreads out through the entire diode. The first solution to confine the recombination processes and light in the active region is to surround the active region with a material that has bigger band gaps and a lower index of refraction. Such a diode laser is called a heterostructure, and they are studied next in some detail.

Double Heterostructure Diode Laser

The energies of electrons and holes near the edges of bands with the relevant wave number can be represented by the following:

$$E_c(\vec{k}) = E_c + \frac{\hbar^2}{2\,m_n}\vec{k}^2 \tag{6}$$

$$E_v(\vec{k}) = E_v - \frac{\hbar^2}{2\,m_p}\vec{k}^2 \tag{7}$$

The variables m_p, m_n are the effective masses of holes and electrons in the semiconductor lattice. E_c is the lowest energy of the conduction band and E_v is the highest energy of the valence band in the active region. The difference of these energies is then the energy of the emitted photon. For GaAs this energy difference is approximately 1.42eV, so in a heterostructure the active medium is surrounded with a material that has a larger and offset bandgap called a barrier region ([10], 619). This keeps the recombination process of charge carriers confined to the active medium because the injected electrons only have enough energy to bridge the band gap energy difference, $E_g = E_c - E_v$, inside the active medium. Figure 2 demonstrates how the band gaps in both the n and p-type barrier regions are larger than the band gap in the active GaAs region, $E_{Fn} - E_{Fp} < E_C - E_V$.

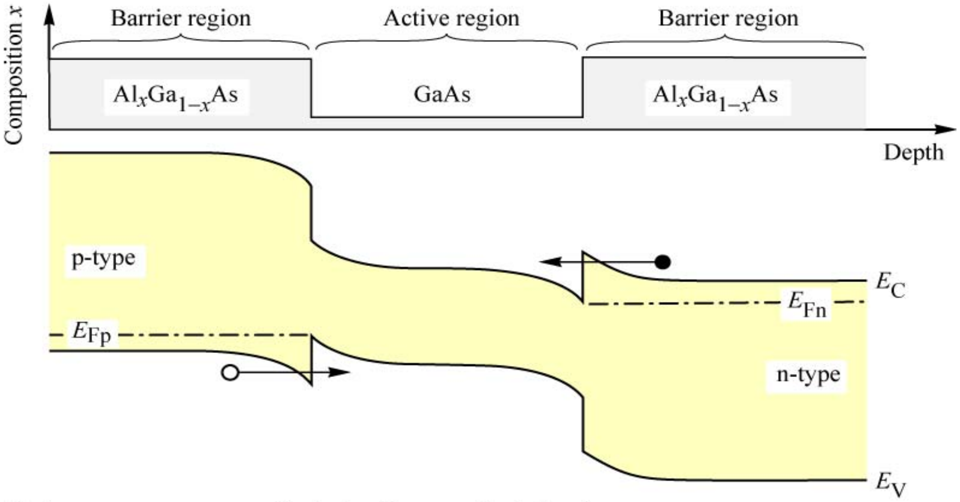

Figure 2: Heterostructure laser composition and energy levels under bias.

The separation between the Fermi levels around the active layer is determined by the injection currents so it is also equivalent to the gain or excitation of the system. The threshold condition of a laser is one where, after a roundtrip in the Fabry-Pérot, the intensity of the light has not changed.

$$R_1 R_2 e^{2(\Gamma G_{th} - \alpha_{\text{abs}})} = 1 \tag{8}$$

R_1, R_2 are the Fresnel reflectivities of the Fabry-Pérot, Γ is the ratio of integrated light intensity that is generated in the core to the integrated light intensity that is kept in the guide, ideally unity. G_{th} and α_{abs} are the threshold gain and total optical losses. Solving the unity gain condition for the threshold gain gives

$$G_{th} = \frac{1}{\Gamma}\left(\alpha_{\text{abs}} - \frac{\ln(R_1 R_2)}{2\mathrm{L}}\right) \tag{9}$$

Permitting a guess of a linear relationship between the gain and the injected charge carrier current density *J*, will help move towards the goal of finding a relationship between the carrier density and gain. This relationship will show an improvement in heterostructure function over the homojunction by significantly confining the charge carriers. A linear relationship also turns out to be a very good guess, so

$$G = \beta\,(\eta_i J/d - J_0) \tag{10}$$

β , J_0 are the gain coefficients that determine the threshold current density. Decreasing the active layer thickness *d*, is an obvious method of boosting gain, and this will useful when considering a quantum well type diode laser. Solving equations (9) and (10) gives the threshold current density requirement ([1], 183)

$$J_{th} = \frac{d}{\eta_i}\left\{\frac{1}{\beta\Gamma}\left[\alpha + \frac{1}{2\mathrm{L}}\ln\left(\frac{1}{R_1 R_2}\right)\right] + J_0\right\} \tag{11}$$

The quantum efficiency is η_i and is determined by the recombination lifetimes of the radiative process to the nonradiative process. We desire high quantum efficiency, that is, recombination should lead to photon radiation and not lattice vibrations.

$$\eta_i = \frac{\tau_{nr}}{\tau_{nr} + \tau_r} \tag{12}$$

Therefore we wish the characteristic radiative recombination time $\tau_{r,}$ to be much less than nonradiative recombination time τ_{nr}. The radiative recombination time depends heavily on the equilibrium and non-equilibrium carrier concentration rates. So the doping of the material, which determines the equilibrium concentration is important, but in the non-equilibrium state at high injected carrier densities the the doping is less important.

$$\tau_r = [B(n_0 + p_0 + \Delta n)]^{-1} \tag{13}$$

$$\tau_r = (B\Delta n)^{-1} \tag{14}$$

The recombination constant *B* depends on the bandgap of the material in question ([7], 15). The equilibrium carrier concentrations for holes and electrons are n_0 and p_0 respectively. Thus a high concentration of injected carriers is necessary to lower the radiative recombination time and achieve a higher quantum efficiency. At a certain level however this relationship fails and other effects caused by leakage currents or high beam intensity will dramatically reduce the quantum efficiency.

The diffusion current is made from the carriers that leak from the active region, and depends on the excess carrier density gradient $\partial(\Delta n)/\partial x$ at the edge of the space charge region in the p doped material.

$$J_n = eD_e \frac{\partial(\Delta n)}{\partial x}\Big|_{x_p} \tag{15}$$

Solving the linear diffusion equation for the excess charge carriers and substituting that into equation (15) gives

$$J_n = eD_e \frac{n(x_p)}{L_D} \tag{16}$$

Where D_e is the diffusion constant of electrons and L_D is the diffusion length related to their lifetime by $L_D = \sqrt{D_e \tau_e}$. The diffusion current can also be related to the offset between the bands of the barrier and the active region by the equation

$$J_n = \frac{eD_e N_c}{d} \left(\frac{p_a}{p_p} \right) \exp\left(\frac{F_{na} - \Delta E_{ng}}{kT} \right) \tag{17}$$

N_c is the density of states in the conduction band of the active material and d is the diffusion length into the p-doped barrier region. The total density of holes in the active and p-doped barrier regions is p_a and p_p respectively. F_{na} is the fermi energy of injected electrons in the active region and ΔE_{ng} is the band offset between the regions. From the Fermi integral, F_{na} , is less than the total band offset energy. As long as the heterostructure was constructed in a reasonable manner, the value of the diffusion current out of the active region will be small ([9], 105). This corresponds to a high level of confinement inside the active region. Reducing this leakage current to below 100 Amps per square centimeter is doable and is a significant improvement over the 10 to 100 kilo-Amps that homostructure lasers of the same type require. Comparisons of the two types of lasers early after the development of the heterojunction, show at room temperature, the threshold current of a heterostructure GaAs laser is lowered by an order of magnitude from a homostructure laser made from the same active material [6].

Quantum Well Laser

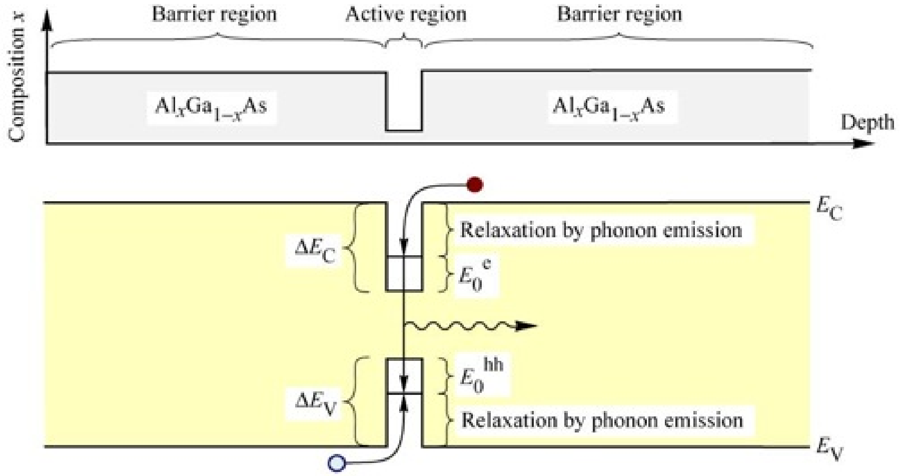

Figure 3: Chemical composition (top) and the band diagram of a GaAs quantum well laser.

The effect of the double heterostructure junction is to create a barrier that keeps the electric interactions in a particularly favored region. The band gap displacements between the active and barrier layers are effectively walls of a quantum energy well. The quantum states however still appear to be mostly continuous as long as the thickness of the active layer is much bigger than the wavelength of electrons in the material. Typical heterostructure lasers have an active medium that is greater than 100nm, but when this thickness is decreased to below 20nm the heterostructure becomes a true quantum well ([9], 144). Equations (10) and (11) are still valid approximations and indicate that by reducing the transverse length of the active region gain is increased and the threshold current is decreased. Figure 3 shows the construction and general function of electrons and holes in a quantum well type semiconductor laser.

In a structure such as a quantum well, the confinement in the transverse direction leads to quantization of the electron energy into subbands. The shape of the conduction and valence bands are still assumed to be parabolic, but the energy levels in them are now discretized [4]. This corresponds to set possible values of *k* in equations (6) and (7). The effective masses of holes and electrons in those equations change as well. The effect on the optical gain properties, from reducing the size of the active medium to the electron wavelength scale, is to remove the possibility of a light field with a wave vector in the transverse direction. Whereas in the bulk heterostructure semiconductor light could be stimulated in any direction, the wave vector is now constrained to the plane normal to the transverse direction of the gap. The optical gain then is now averaged over only two directions. Equation (6) becomes

$$E_e = E_z + \frac{\hbar^2}{2\mathrm{m}^*}(k_x^2+k_y^2) \tag{18}$$

The z direction is taken to be the transverse direction and the mass in the second term is the appropriately calculated mass of the thermalized electron ([7], 180). A similar change can be made to equation (7) but the effect of multiple valence bands, not as important in bulk material, becomes apparent. The lower band depicted in figure 1 is actually split into multiple different bands. To represent this effect, the v subscript of the first term in equation (7) is now an index for each valence band; the hole mass is indexed as well. The heavy and light hole bands are the two most important in the direct transitions that result in radiative emission.

The states of an electron as calculated from equation (4) are now entirely quantized. The total gain from the active material then is the sum of the gain for each transition type, which is no longer assumed to be just between conduction and valence bands. Transitions can now occur between different states in the conduction band to different states with different valence bands. Heavy hole transitions occur with the greatest probability, but considering all energy level transitions, the gain is

$$g(E) = \int_{\infty}^{\infty} g_{\max}(E)(f_c - f_v)L(E)dE \tag{19}$$

The g_{max} is the negative of the cavity losses and the new function L(E) arises from taking into consideration the effects that cause line width ([9], 161). The line width is more important on the quantum scale because the sharp transitions previously assumed are not actually physical. Carrier scattering of two types causes the a Lorentzian like line width. Carrier-carrier scattering and phonon-carrier scattering, crystal vibrations, are the culprits.

Quantum well lasers have several advantages that come from considering these new effects. For instance the effect of decreasing the threshold current needed for gain also decreases the line width of the output light. An input current density J leads to an excess charge carrier density Δn, which determines the difference between the Fermi energies in the conduction and valence bands ([10], 635). The smaller currents allows one to more narrowly select the difference in Fermi energy thus permitting fewer transitions. This effect also increases the overall quantum efficiency of the laser.

The situation can be complicated further by an effect called strain. GaAs and AlGaAs have different crystal lattice constants. The different separation distances between atoms in the two types of crystals is on the same length scale as the thickness of the GaAs active layer. The lattices when brought together will become strained due to compression or tension from the opposite crystal. The strain in the lattice causes the density of states in the valence band to be altered as well as changing the gap energy between the conduction and valence bands ([9], 167). The change in the distribution of states and the Fermi levels will have an effect on the gain of the quantum well. For the right selection of materials the gain and quantum efficiency of the system can be altered in a favorable way by inducing strain on the quantum well.

Quantum Well Optical Effects

Diode lasers experience strong dispersive effects in response to the optical gain inside them including a strong amplitude-frequency coupling, which can be described by means of Henry's linewidth enhancement factor. This factor describes the change in the index of refraction as it relates to changes in the gain or absorption of the medium as carrier density varies. Furthermore the factor is itself a function of the frequency and carrier density in the medium. Changes to the index of refraction alter the behavior of light in diode lasers in two ways. Changes to the index of refraction can cause mode pulling or pushing, frequency changes, in each round trip inside a Fabry-Pérot. Index of refraction is also highly important to containing the guided modes inside the semiconductor, so, especially for weakly index and gain-guided devices, changing the index of refraction can significantly alter the optical gain in the medium [2].

The p-n junction itself significantly increases the index of refraction to the volume directly surrounding the junction. This change is due to the changes in the density of states and the altered fermi levels there discussed above. This increase in the index creates a natural waveguide there to direct the light created in that region. The effect is fairly weak however and the light propagates some way into the cladding around the active layer. The optical confinement factor Γ, varies inversely with the threshold gain and current, equations (9) and (11). Then in the case of a heterostructure it is important to choose materials for the barrier that have low a absorption coefficient and high index of refraction. The right material choices of the barriers are the largest factors in the improvement in optical gain and quantum efficiency ([9], 112).

One simple method to improve the optical confinement, gain and efficiency is to stack multiple quantum wells close to each other. Figure 4 illustrates a possible configuration of a multiple quantum well arrangement using a couple of different types of active layer. By altering barrier well barrier the optical confinement is increased because the effective index of refraction increases with the multiple low-high index boundaries ([9], 167). An additional benefit of a multiple quantum well laser is increased power output. Each additional quantum well increases the chance of capturing more energetic electrons as well as increasing the over all size of the active medium without increasing the size of any of the active layers ([7], 191). The downside to the increased power output is the need for an increased carrier density in the active region because each well requires its own minimum carrier density. This can raise the threshold current substantially.

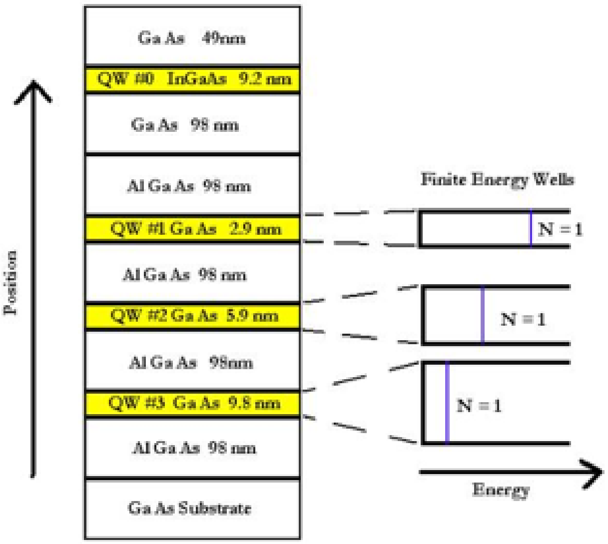

Figure 4: A possible configuration of a multiple quantum well laser diode.

There are however unique limiting factors to the maximum output power of a diode. Increasing the current, thereby increasing the carrier density, will increase the gain of the laser, but at a certain point carrier saturation will cause catastrophic optical damage (COD). The material surrounding the active region of the laser can heat for several reason thus causing the bandgap to shrink. When the band gap is so small that it can no longer prevent excess carriers from escaping the active region, current flows freely. High current will cause burns at the surface of the crystal on the Fabry-Pérot facets of the semiconductor ([7], 438). Heating around the active layer can occur because the barriers themselves may absorb electrons transferring their energy into heat phonons in the crystal. Another source of heat involves the actual composition of the facets themselves. The break in symmetry of the lattice at the edges of the diode creates a different band structure at the facets. The band structure at the facets is changed so that it will absorb some of the photons generated in the active region and, the electrons that relax there will mostly release phonons which heat the structure ([9], 312). The most common solution to both these problems is to coat the facets with material that mitigates these effects by altering the band gap transitions and protects them from heating.

Other Diode Laser Advancements

The latest developments to semiconductor laser technology continue to further reduce the threshold current, increase the maximum power output or extend the lifetime of the diode. Quantum well lasers have become quantum wire and quantum dot lasers with energy gaps determined by the dot dimensions. These developments have made higher frequency light, in the near UV range, from diode lasers readily achievable. Other techniques have improved diode laser output modulation for high signaling rates. Improved modulation has overcome an effect called chirp that results mainly from changes in the index of refraction over the very short output pulses. The major improvements to peak output intensity have come from coatings to the facets that reduce the amount of non-radiative recombination. The overall intensity diode lasers are capable of reaching however is still determined by the amount of heating the junction and facets can take before failing.

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Figures

Figure 1: Wadsworth, W. http://www-alphys.physics.ox.ac.uk/research/groups/laser/diodes.html

Figure 2: Schubert, F. http://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap04/chap04.htm

Figure 3: ibid.

Figure 4: http://webphysics.davidson.edu/course_material/ModernPhysicsLabs/optspect4.html