REPORT
List of failure modes and mechanisms in Laser Diodes

Part 1/2

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Note.

This document will mostly (but not only) refer to:

1) M. Fukuda: “Degradation and Radiation Damage in Laser Diodes – the Relationship between Space and Telecom Reliability”, invited talk at ISROS 2010 (attached to this document)
Introduction

The first choice in listing reliability issues for laser diodes, as for any other device, is to start from causes or from effects. In reliability words: failure mechanisms (physical causes) or failure modes (observable effects).

The complexity of the task, in any case, may be summarized by the following figure (Fukuda)

**Main degradation part and characteristics change**

Here M. Fukuda, probably the maximum authority in semiconductor laser reliability, collects and links the state of the art (updated at 2010) for failure mechanisms (right side: causes), localization on the laser chip (central: Degradation part) and failure modes (left side: Characteristics change).

The central column refers to internal laser chip technology, whose highlights will then be now recalled, being completely evident that here is the link between modes and mechanisms.
A summary of laser diode technology

1. Epitaxy and heterostructures

When we consider the vertical stack of epitaxial layers, all laser diodes share the common vertical features along a line that crosses the optically active part of the device: a Double Heterostructure (DH) pn junction.

- The reason for such a structure is that photons are created by electron-hole recombination in direct band-gap semiconductor crystals.
- In order to have many photons, it is necessary to bring many electrons and many holes to meet in the same place, and to help them to the maximum extent to recombine.
- The first step, that is to bring electrons and holes to meet, is easily obtained in a forward biased pn junction. Anyway, in standard ideal junctions (pn omojunctions) electrons and holes run in opposite directions but recombine in separate places: holes in the neutral n region, and electrons in the neutral p region, skipping the whole depletion layer, where jointly their densities p, n and their product pn are maximum. (see appendix 1)
- The second step is to insert a thin layer (the active layer) of a different semiconductor material, compatible with the surrounding ones, and with a band gap $E_g$ as smaller as possible than in the rest of the material. The reduced band gap makes the recombination rate higher than in the other material, when the same electron and hole densities populate the depletion region. It follows that, different from a standard homojunction diode, strong recombination is forced inside the active layer, despite its total immersion in the middle of the much wider depletion region. (see appendix 1).
- The result is that the emitted light spectrum will be completely dominated by the sole characteristics of the active layer (see my previous report "Spectral considerations on Fabry Perot and External Cavity lasers" issued on September 12th, 2011). The most significant feature is that the peak energy $h\nu_0$ of the emitted photons will equate, within few percent, the band gap energy $E_g$ of the active material.
**Epitaxy** is, of course, the solution for building such a heterostructure. Some golden rules hold for the epitaxial process for laser diodes (appendix 2 adds some details):

1) All materials must share the same crystal structure (lattice), the same orientation and the same lattice constant. *The most part of suitable materials has a zincblende structure, that is an fcc lattice with a binary atom basis.*

2) A substrate, some hundreds micrometers thick, must be provided, whose role is to make the structure robust and handling. It MUST be a stoichiometric material, because of the cost and the technical difficulty to handle non-stoichiometric layers at thicknesses larger than about one micrometer. For vertical diodes, it must be conductive. It is usually $n$-doped.

3) Three layers must then be epitaxially grown on the substrate: one confining layer (n-type), the active layer (usually undoped) and a second confining layer (p-type). All three can be non stoichiometric (ternary or quaternary compounds).

   *(for epitaxy of ternary and quaternary systems, see f.i. Simon Sze “Physics of Semiconductor devices” part V, Wiley)*

4) The confining layer must have a band gap as higher as possible than the band gap of the active layer. *This ensures both the electron-hole confinement and also the optical confinement of the created photons, building up an efficient optical waveguide.*

5) A cap layer is usually grown on the top, to ease the electric ohmic contact of the upper metallization.

6) The band gap of the substrate is of minor importance for edge emitters. For vertical devices (i.e. VCSEL) must have a band gap larger than the active layer, to avoid photon absorption.

**Chemistry** must also be developed, able to selectively etch even a single layer without affecting the other ones. This in order to ensure patterning during some particular non planar growth (as for buried crescent structures, see later) or to etch grooves from the top surface to confine current injection on limited areas (see later).

*To have a glance at the technological complexity of chemistry for photonics, see f.i. a funny but not stupid website, appreciated by my students:*


At this point, the common vertical structure of any laser diode appears as in the next figure, which updates the previous image.
2. Lateral confinement

For the same reason that led to require a substrate (the optical active elements: active and confinement layers, are too thin to stand alone), the lateral size of any laser chip is much larger than the strictly needed one for laser operation. The optically active region must then be laterally limited.

Roughly speaking, two main reasons lead to require small vertical and lateral size for the optical cavity of a laser diode:

a) In order to keep the cavity unidimensional (see my previous report “Spectral considerations on Fabry Perot and External Cavity lasers”) the vertical and lateral sizes of the region where photons are produced must be comparable with the wavelength of the emitted light (in order to suppress higher harmonics), that means must lay in the micrometer range. It is not a problem for the thickness, that is so thin to be comparable with the electron wavelength, but is a problem for the lateral extension, that in a normal chip is several tens of a micron or larger.

b) The smaller the volume of the active region, the lower the current required to pump it up to the laser threshold.

Many different solutions have been developed during the decades of the laser diode history.

Here, based on the Fukuda’s paper and with some integrations, a list of solutions for the edge emitters will be reported.

2.1 Current confinement

One of the most practical ways to get light from a reduced portion of the active region is to feed with current only a portion of the upper surface. The simplest solution would simply pattern the upper metal in a stripe shape.
This solution unfortunately has many disadvantages:

1) It reduces excessively the top metal surface, and makes impossible wire bonding
2) The exposed remaining part of the cap layer must be protected by a passivation, that should be then patterned to open a window for wire bonding.

2.1.1 Oxide Stripe

The closest practical alternative has been a quite popular technology for GaAs based devices, the Oxide Stripe geometry.

2.1.2 Ridge structure

The evolution of that solution has been the ridge structure, where the cap layer is first patterned, and then the exposed part of the underlying p-confinement layer is significantly reduced, also by chemical etching. The result is a sort of funnel that focuses the current onto an even more limited part of the active layer. The silicon oxide has been often replaced by silicon nitride.
2.1.3 Zn-diffused planar

A third way is to replace the p-cap layer with a n-cap layer. This would create a reverse-biased junction that would block any current from flowing into the device. A Zn diffusion, limited to the current injection area, locally destroys the new junction and creates an ohmic path from the upper metal and the p-confinement layer.

2.2 Light confinement

A second approach is to physically limit the extension of the light producing area.

2.2.1 Proton bombarded
A “brutal” mode is to leave the whole active layer in place, but to destroy its optically efficiency by proton bombardment of the sides of the wanted active area (it is sufficient to shield it during the exposure to protons).

This will cause parasitic resistive conduction across the bombarded regions, that acts as a current shunt, parallel to the surviving active diode. The very low impedance of the diode under forward bias will allow its current to rapidly dominate over the shunts.

Moreover, and even more important, the damage of the lattice perfection will enormously enhance, inside the bombarded parts of the active layer, the non radiative recombination. This, in turn, will dramatically reduce the number of photons, and lead the bombarded material to change from gain to absorption for light. This extinguishes the light that attempts to propagate laterally, and suppressed the side modes of the cavity.

### 2.2.2 Buried Heterostructure (BH)

A much more sophisticated solution, usually created in the InP/InGaAsP system, cuts the structure, as for the ridge geometry, but allows the etch to pattern the whole p-cap layer, the whole upper p-confinement layer, the whole active layer and, finally, part of the underlying n-confinement layer.

Such a deep etch will usually require different steps for each layer (here chemistry enters into play at its maximum extent), and many of them employ anisotropic etches (that, acting at different speeds on the different crystal orientations, produce inclined plane surfaces).

The last etch, usually isotropic, leaves a curved surface, caused by the central surviving column. At this point a sequence of p-InP, n-InP, n InGaAsP layers is epitaxially re-grown.

The result is a device where side currents still survive, all across $pn$ InP homojunctions. Here the lower impedance of the central Double Heterostructure p-InP/InGaAsP/n-InP allows the active region to collect more and more current as injection increases.
2.2.3 Buried Crescent (BC) or v-grooved substrate BH

Finally, a similar approach, based on a more complex sequence, leads to the Buried Crescent structure, here reported from the Fukuda’s paper. From the topological and electrical point of view, it operates as the previous BH structure.

A mixed use of the various solution can be adopted, as in the following image, where a Buried Crescent structure is coupled with the Ridge technology (from Vanzi, Tolouse, ref.3).

A peculiar feature of the BH solution is that the active region is not only thin but also narrow (and long), completely surrounded, laterally and vertically, by higher bandgap material.

This makes the active stripe optically guided also laterally. This means that the active stripe could designed be not straight, forcing the light to follow its shape, as in an optical fiber. This is useful when external cavity configurations are employed (as for some tunable lasers), where the optical resonances internal to the chip must be avoided (while they are requested for internal cavity solution, see next chapter).

The following picture, from my previous report on the Emcore ITLA device, shows an optical view from the top of a laser chip, inserted between two external lenses, and the bent thin line visible on the chip individuates the guided active stripe, with a transverse structure probably quite similar to the SEM image reported in this page.
3. Quantum Wells (QW)

The spectrum of a laser diode comes out from the optical frequencies belonging to its spontaneous emission range (see my previous report: “Spectral considerations on Fabry Perot and External Cavity lasers”), that corresponds to the LED regime that holds for current intensities lower than the threshold current $I_{th}$.

This spontaneous emission spectrum, in turn, is quite sensitive to temperature.

*This is due to two reasons:*

  a) Temperature modulates the amplitude of the band gap
  b) Temperature affects the density of electrons and holes

*Both effects contribute to shift the peak and the shape (width) of the spectrum.*

But when the thickness of the active layer becomes so small to be comparable with the De Broglie wavelength associated to both Bloch electrons and holes, quantum effects appear, that result in *quantization of both electron and hole energy levels* inside the active layer.

This reduces the influence of temperature to the only thermal expansion of the thickness of the active layer, that is by far smaller than the previously indicated effects.
In this way, wavelength is much more stable with respect to temperature..

### 3.1 Multiple Quantum Wells (MQW)

One disadvantage of creating an extremely thin active layer is that it reduces the fraction of electron-hole pairs that are forced to recombine inside it. The problem is solved by creating multiple quantum wells, that is a stack of alternating quantum wells and thin confinement layers (usually undoped). The stack is still so thin to remain quite well immersed inside the depletion region of the $pn$ diode. Careful design can take full advantage of the resonances that such a periodic structure can activate, and further enhance both recombination efficiency and frequency selection.

### 3.2 Strained Lattice QW

The extremely small thickness of a QW, that corresponds to few crystal planes, allows to create quite artificial situations, where a crystal that should have a smaller lattice constant than the surrounding material (the upper and lower confinement layers) is forced to enlarge its spacing, to fit the dominant periodicity of the more massive parts.

This solution makes accessible unusual values for optical parameters as quantum efficiency, refractive index (and then optical confinement) etc. It is usually employed in the InGaP /GaAs systems.

### 4. Distributed Feedback (DFB)

The next chapter will deal with the Fabry-Perot cavity, where light reflection inside the chip selects several possible optical frequencies for laser emission from the initial spontaneous spectrum (see also the report: "Spectral considerations on Fabry Perot and External Cavity lasers").

In order to select one specific emission line among the many possible ones, one clever solution is to introduce a corrugated heterostructure inside one of the confinement layers. This structure is made of two layers, both with a bandgap larger than the energy of the photons emitted by the active region, and with different refractive index. Their interface is shaped (by means of interferential lithography) in a periodic undulation. The effect of such a structure is very well described by the following Fukuda’s slide.
Here it is shown as the optical field due to the photons created inside the thin active layer extends its tails deeply into the confinement (guide) layers. The longitudinal propagation of such an optical field then senses the corrugation (grating).

It is a classical result of the wave propagation theory, first introduced by Bragg for x-rays and then by Block for the Schroedinger waves, that a back-reflected wave sets up when the optical propagating wavelength $\lambda$ is equal to the periodicity $a$ of the grating.

The complete theorem states that this holds also for \( \frac{\lambda}{2} = \frac{a}{m} \), where $m$ is an integer. But for laser diodes, the other possible wavelengths lay out of the available spectrum.

This structure, not only selects a wavelength, but is also much more stable with respect to temperature, as reported by Fukuda in his other slide, here reported.
5. Longitudinal confinement. Fabry-Perot optical cavity.

No matter the solution adopted for the lateral confinement, and after having appreciated the
common vertical structure for any laser chip, the longitudinal dimension remain to play the role of
the one-dimensional optical cavity.

Its extension (in the order of many hundreds of a micrometer) is by far larger than the other two
dimensions.
Its length \( L \) plays a fundamental role for the optical modes (see my previous report “Spectral
considerations on Fabry Perot and External Cavity lasers”).

Within this cavity light must undergo several reflections before exiting.

The opposite facets of the longitudinal cavity must be planar at an optical level of accuracy. This is
easily achieved by cleaving them along the preferential crystal directions (usually [110] planes).

The difference in the refractive index between the active material \( (n) \) and vacuum \( (n_0=1) \) introduces
a certain amount of natural reflectivity (see my previous report “The Double Etalon filter in Vernier
configuration”)

\[
R_0 = \left( \frac{n - 1}{n + 1} \right)^2
\]

that, on the other side, for standard semiconductor does not exceed the value of 40%.
This is NOT sufficient for laser requirements.
A low reflection coefficient means high total losses, that, in turn, increases the value of the threshold current.

The standard configuration of an edge emitter laser calls for different reflection coefficients.

Light is indeed allowed to exit the cavity from both its opposite sides. From one of them the output
light is collected (or directly by a fiber or by means of an output window, possibly coupled with
some focusing elements).
From the other side a minimum optical power is sent to a photodetector (a diode).
The role of the monitor diode (conventionally assumed to be on the back of the laser diode, being the output facet on its front) is to supply the direct measurement of the emitted optical power required to provide a feedback for constant-power operation. Its function does not require as many light as the output system, and then the back facet is highly (but not totally) reflecting, while the front facet is mostly reflecting, too, but at a minor extent.

For this reason the two facets are often indicated as back and front mirror, respectively. On a reliability ground, the different reflectivity means that the back mirror is usually hotter than the front mirror.

The needed reflectivity is achieved by coating both facets with a carefully designed stack of dielectric layers, differing by refractive index and thickness.

(see my previous report “The Double Etalon filter in Vernier configuration”, part 3, last chapter, where the multiple stack of dielectric layers is shown for an external reflecting element)

The final configuration, that is the simplest one for a laser chip, is known with the name of Fabry-Perot.

6. Chip assembly and packaging (requirements)

Even for the simplest laser chip, its assembly is a delicate task.

1) The device must be firmly assembled in front of the monitor diode.
2) For both, wire bonding must be performed.
3) If a fiber or a focusing element are included, they must be positioned with micrometric accuracy.
4) Heat control is often included by means of Thermo Electric Coolers (TECs), in order to avoid any shift in the optical frequency due to the thermal dependence of the refractive index on temperature.
5) A clean ambient must be hermetically sealed around the device, to avoid particle or reactive gas interference with the highly dense output optical beam.
7. Summary of technology

At this point, all parts in a standard document dealing with laser technology should be identified. Referring again to Fukuda

- the central vertical stack
- the side blocking regions
- the substrate
- the upper and lower metallization
- the indication MQW for the active region
- the corrugation (grating) that reveals the example as a DFB device

### In Silica Fiber Systems

- **1.30 – 1.65 μm band**
  - strained QW InGaAsP/InP laser
  - strained QW InGaAlAs/InP laser
  - strained QW InGaAs/InP laser

- **0.98 μm band**
  - strained QW InGaAs/GaAs laser

### In Plastic Fiber Systems

- **0.78 – 0.85 μm band**
  - (strained QW) AlGaAs/GaAs laser

- **0.65 μm band**
  - strained QW InGaAlP/GaAs laser
Operating characteristics

1. Operation

As it is well known, a laser diode is operated by adding a modulation current to a DC current sufficient to keep the diode above (or close to) the threshold for laser emission.

Direct modulation of semiconductor laser

The DC current, indicated as operation current, should generate a constant and stable optical power, modulated in turn by the variable current variations.

Anyway, such an indirect control of the optical power, that may suffer for any phenomenon that can change the photon generation rate (degradation mechanism, temperature) is usually refined by the feedback provided by the monitor diode.

In this way, the current that is electronically stabilized is the monitor current instead of the laser current, which more efficiently ensures the constant optical power operation of the laser.

This means that, when required, the DC laser current may be changed in order to keep constant the optical power.

Monitoring the time variation of the operation current is a tool for inspecting laser degradation.

2. Characteristics and general degradation mode

Another slide from Fukuda illustrates this last point.

In the first graph, the typical $P_{OUT}(I)$ characteristics of a laser diode are first plotted for the initial state (lower curve), and then after some evident degradation that led the threshold current to increase and the slope (efficiency) to decrease.
The other graph, on the right, reports the progressive time evolution of the current (operation current) required to keep the optical power constant.

The successive image from Fukuda illustrate an experimental example.

For the sake of completeness, this last figure introduces the failure criterion, that is the maximum acceptable level for the increase of the operating current, defines the temperature (70°C indicates that it is an accelerated life test at constant power and high temperature), and the constant power set for the experiment.

Finally, the two straight lines tracing the slope 1.0 and 0.5 aim to show how the experimental evolution of $I_{op}(t)$ starts with $I_{op}(t) \propto t$ at the beginning, and then reduces to $I_{op}(t) \propto \sqrt{t}$ for longer times.

This is the typical time evolution of 1D diffusion kinetics.

It is interesting here to observe that such a result can only suggest that something is moving according with the Fick’s law for diffusion. Nothing is said on what is diffusing and where. Modelling and failure analysis must give the answer.
3. Technology and modelling

When we consider the many technologies for a laser diode, as listed before, we can realize as all those that employ light confinement are electrically equivalent to the ridge structure, and that the two BH solutions are, under the electrical point of view, the same.

When we then look at the two solutions, we see that the two are essentially the same:

Here, a series resistance collects all ohmic effects of the upper and lower contacts, the side diode collects the whole conduction outside the active region, its resistance gives account for the path travelled by current to reach these side areas, and a shunt resistance is also added (on the left) to deal with possible vertical surface conduction on the chip edges (and usually is no lower than several MOhms).

The central element, given by a double “diode” is a new symbol that describes a) the current flowing across the active area without any recombination (the white diode), that is a pure Shockley diode and b) the pure laser diode, whose characteristics are that of a standard Shockley diode for voltages lower than the threshold voltage $V_{th}$ and a voltage regulator $V = V_{th}$ at higher injection levels.

The theory of such a device is summarized in my previous report “DC measuring laser diodes”, and more extensively in
It is important to realize that the current $I_a$ flowing in the “pure laser diode” according to that model, is a function of the total current $I$ injected into the laser that completely coincides (apart from a coupling constant) with the optical power detected by the external monitor diode.

Equation for the whole circuit are available (see the quoted reports). The connect the experimental curves to circuit parameters. Circuit parameters, in turn, refer to technological elements. Reading experimental variations leads to classify the failure modes in terms of possible failure locations, that is the starting point to identify failure mechanisms.
Appendix 1 Electron and holes in a forward biased $pn$ junction.

In a pn omojunction, the distance between the limits (edges) of the conduction and the valence bands is fixed (it is equal to the band gap $E_g$).

The density of holes $p$ and of electron $n$ is proportional to the exponential of the distance of the Fermi level from the valence band, divided by $kT$ (holes), and from the conduction band (electrons).

$$n = N_c \exp\left(\frac{E_c - E_F}{kT}\right) \quad p = N_v \exp\left(\frac{E_F - E_v}{kT}\right)$$

At equilibrium, the Fermi level is a straight line, and the product $pn$ is a constant everywhere, independent on the local doping.

$$pn = N_c N_v \exp\left(\frac{E_c - E_v}{kT}\right) = N_c N_v \exp\left(\frac{E_c}{kT}\right)$$

When a forward bias $qV$ is applied, the step between the $n$ and $p$ sides lowers, electrons and holes can flow on opposite sides, crossing the depletion layer.

The Fermi level becomes meaningless, because it is only defined at equilibrium.

Two separate levels $\phi_n$ and $\phi_p$, called quasi-Fermi levels, are introduced to represent the new electron and hole densities.

$$n = N_c \exp\left(\frac{E_c - \phi_n}{kT}\right) \quad p = N_v \exp\left(\frac{\phi_p - E_v}{kT}\right)$$

Now, more electrons and more holes populate the structure. Recombination tries to destroy their excess.

The hypotheses that
1) far from the junction all the densities return to their equilibrium values
2) no recombination occurs inside the depletion layer

lead to the following modified figure, where recombination of electrons and holes takes place at the edges of the depletion region, where the green and red lines of their quasi-Fermi levels only deviate from the straight trend.

This situation is negative for creating photons because of the large volume involved in their production, that makes quite difficult to achieve those photon densities that can start the laser effect.
When a lower band-gap material is inserted inside the depletion region, the electron and hole densities, injected by the $p$ and $n$ sides of the forward biased junction (that now is a Double Heterojunction) are so excessive with respect to their local equilibrium values that strong recombination occurs.

It is important to recognize that, despite this nice solution:

1) not all charges will recombine inside the active layer: some will cross it and continue their trip as in a “normal” diode. It will give rise to a Shockley current that will stand together with the recombination current produced by the active layer.

2) not all recombination inside the active layer will produce light. Some will take place in non-radiative way. This is the foundation of the concept of quantum efficiency $\eta_q$: it is the fraction of the total number of recombination events that will actually produce light. Counting the number of radiative recombination events per seconds will count the number of produced photons: one recombination-event= 1 photon.
Appendix 2. Epitaxial rules for DH lasers

Let us consider the following graph.

It defines the two quaternary systems $Ga_x In_{1-x} As_y P_{1-y}$ and $Al_x Ga_{1-x} As_y Sb_{1-y}$.

For each system, any choice of $x$ and $y$ identify a quaternary compound that crystallizes in the zinc-blende form (face centered cubic, fcc) with binary basis made of the couple AB of different atoms. The index $x$ indicates the fraction of, say Ga and In, that fill the A position, while $y$ does the same for As and P in the B position into the basis of the crystal.

Let us consider the first one, highlighted with a red boundary.

All possible compounds must lay inside the bounded area, or on its boundary.

It locates four stoichiometric compounds ($GaP$, $AlAs$, $GaAs$, $InAs$) along the boundary.

(It should be clear that in this case, for instance, $GaP = Ga_{1/2} In_{1/2} As_{1/2} P_{1/2}$)

For each compound, the horizontal axis gives the lattice constant $a$, the left vertical axis the corresponding amplitude of the energy gap $E_g$ and the right vertical axis reads this value in terms of optical emitted wavelengths.

Before trying to design a true laser chip, let us try to find the composition (that means the values of $x,y$) of a generic quaternary compound.

First of all, any point on the boundary has a measurable distance from the closest pair of stoichiometric compounds, that always share one or the A or the B atoms.
For instance, in the following figure, two points have been identified on the boundary, and their composition has been calculated by means of simple proportionality: the closest the point to one binary compound, the higher its relative abundance in the ternary.

\[ \text{GaP} = \text{Ga}_1 \text{In}_0 \text{As}_0 \text{P}_1 \]

\[ \text{Ga}_{0.25} \text{In}_{0.75} \text{As}_0 \text{P}_1 = \text{Ga}_{0.25} \text{In}_{0.75} \text{P} \]

\[ \text{Ga}_{0.7} \text{In}_{0.3} \text{As}_1 \text{P}_0 = \text{Ga}_{0.7} \text{In}_{0.3} \text{As} \]

The two points have been selected on the same vertical, keeping in mind the next construction of an epitaxial structure: having the same crystal lattice, they \textit{must} share the same lattice constant \( a \), in order to allow defect-free epitaxy.

At this point, any intermediate point along the vertical line joining the two given points is calculated by the same means.

\[ \text{GaP} = \text{Ga}_1 \text{In}_0 \text{As}_0 \text{P}_1 \]

\[ \text{Ga}_{0.25} \text{In}_{0.75} \text{As}_0 \text{P}_1 = \text{Ga}_{0.25} \text{In}_{0.75} \text{P} \]

\[ \text{Ga}_{0.49} \text{In}_{0.52} \text{As}_{0.05} \text{P}_{0.95} \leftarrow \text{GaAs} \]

\[ \text{InP} = \text{Ga}_0 \text{In}_1 \text{As}_0 \text{P}_1 \]

\[ \text{Ga}_{0.7} \text{In}_{0.3} \text{As}_1 \text{P}_0 = \text{Ga}_{0.7} \text{In}_{0.3} \text{As} \]

Now, we are ready to design a laser diode, following the rules given in the main text:

1) Select the emission wavelength on the right vertical axis.
2) Draw an horizontal line passing for that point.
3) Search for a possible substrate drawing vertical lines across the binary compound and looking for a cross point with the previous horizontal line that lies inside one of the quaternary systems.
4) Select the compound (ternary or quaternary) corresponding to that crossing point. This is the active material.
5) Select on the same vertical line of the crossing point the highest possible point that belongs to the same system. Often it lays on the upper boundary. That is the material for the confinement layers.
The following example deals with a 1300 nm laser diode. It is clearly grown on an InP substrate, has a quaternary active region and again InP for the confinement layers. This agrees with the figures, for instance, in the previous chapter 2.2.3.

For a rough estimate of the compositions, we can appreciate that the point where the lower boundary crosses the InP vertical line is a little bit closer to InAs than to GaAs, that leads to a ternary $Ga_{0.45}In_{0.55}As$.

The active region is at a distance 1/3 from this ternary, whose abundance is then roughly 2/3 with respect to InP at the upper extreme.

\[
Ga_{0.45}In_{0.55}As_{1.00}P_{0.00} \times \frac{2}{3} + \\
Ga_{0.00}In_{1.00}As_{0.00}P_{1.00} \times \frac{1}{3} = \\
Ga_{0.30}In_{0.70}As_{0.67}P_{0.33}
\]

![Diagram](image-url)