Capabilites and Reliability of LEDs and Laser Diodes

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In general, high temperature testing is used to determine LED and laser diode lifetimes, even though laser diode failure mechanisms are more sensitive to increases in current density. As a measured parameter of degradation, the current density is of great significance when searching for failure modes in a laser diode. Raising the current density however, is not really indicative of lifetime since it is more likely a situation to be avoided than one that simulates normal lifetime degradation. The reliability of semiconductor sources is very dependent on the degradation modes. This report intends to summarize some of the degradation modes and capabilities of typical LEDs and laser diodes currently used in many communication and sensing systems.

LED's are typically used in multimode transmission systems where data rates no larger than 50 Mb/s are required. They have larger spectral widths and can add to the problem of dispersion in communications systems. Laser diodes are used in systems that require coherent and often single mode light such as high data rate communications and sensing applications. In comparison to laser diodes, LED's can generally be driven harder, are less expensive, have lower power, have larger emitting regions, and longer lifetimes. Lasers, unlike LED's will not operate below a threshold current. Meaning, only when the threshold current is reached will the diode commense lasing (functioning). As mentioned previously, LEDs and laser diodes are temperature sensitive when considering overall lifetime, for example, operating a laser diode at 10 °C higher than rated will half the life of the diode. Also a laser usually will stop functioning at 100°C. The degradation modes that result in failures or gradual degradation of these devices can be modelled using Arrhenius relationships where each degradation mode carries a specific activation energy. For example in reliability tests in which lifetime is based on temperature aging the relationship is life = $A\, e^{Ea/kT}$.

Capabilities:

Table 1: Comparison of Typical Parameters of Interest for LEDs and Laser Diodes

Attribute/ Parameter	**LEDs**	**Laser Diodes**
Radiative Recombination	Spontaneous Emission	Stimulated Emission
Particle Phase	Incoherent	Coherent
Polarization state	Randomly polarized	linearly polarized
Direction	Random	linear
665 nm	GaAsP	GaAlAs
800-930 nm	$Ga_{1-x}Al_xAs$	$Ga_{1-x}Al_xAs$
1300, 1550 nm	InGaAsP	InGaAsP
Spectral Width	$\Delta\lambda \approx 1.45\ \lambda^2\ kT$ λ in μm, kT in eV, k = Boltsman's constant, T = junction temp	
Spectral Width, GaAlAs	10s of nm	< 1.5 nm
Spectral Width, InGaAsP	surface emitting, 100 nm edge emitting, 60 -80 nm	.1 to 10 nm
Significant Parameters	BW vs Power BW increases at the expense of power	Threshold current, Index guided: 10 to 30 mA Gain guided: 60 to 150 mA
Reliability lifetimes	10^5 to 10^8 hours	10^5 hours
Temperature Effects	increases wavelength by .6 nm/ °C	wavelength varies by .25 nm/ °C threshold current rises by .5mA/°C
Rise Time	1 to 100 ns	< 1 to 10 ns
Output Power	10 - 50 (highpower) μW	1 - 1000 mW
Modulation	3 Mhz - 350 Mhz	> 350 Mhz

In general the bandwidth-rise time relationship is calculated as BW = .35 / rise time.
x is between 0 and 1 in $Ga_{1-x}Al_xAs$

Table 1 summarizes available information on a wide range of LEDs and laser diodes. Specialty devices are not included in this summary and the parameters specified are highly generalized. This data is included as a reference when considering which device, due to attribute or parameter, is most useful for the application.

Degradation Modes

The main degradation modes are: dislocations that affect the inner region, metal diffusion and alloy reaction that affect the electrode, solder instability (reaction and migration) that affect the bonding parts, separation of metals in the heat sink bond, and defects in buried heterostructure devices. These modes are enhanced by current during ambient temperature operations. Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes.

Degradation of the Inner Region:

Point Defects lead to Dark Line Defects

The main causes of degradation in the inner region is directionally dependent on the crystal structure as well as dependent on the material used for the source. In particular dislocations along the 100 direction grow as a result of interstitial atom or vacancy point defects. AlGaAs/GaAs show a much higher rate of dislocation growth than sources fabricated in InGaAs(P)/InP. In general, the longer the wavelength response of the material, the less sensitive it is to this point defect. Point defects can also lead to a slow degradation or a rapid degradation when the defect leads to a plane defect in the crystal structure. Improving crystal growth techniques is the only way of making them less likely.

Other Types of Dark Line Defects

Dislocations along the 110 crystal axis will grow and form as a result of mechanical bond stresses. The result of both types of dislocations are Dark Line Defects (DLD) and induce rapid degradation of the device. Another degradation in InGaAs(P)/InP sources is precipitation of host atoms that result in an elevation in pulse threshold current (driving current required for lasing). The higher this current is driven the faster degradation of other mechanisms will occur as a result as well as dark line defects. In looking for these types of degradation mechanisms it is more revealing to monitor the threshold current as opposed to the output power. The threshold current is more sensitive to defects than the output power. As the current is driven to saturation, noise will develop in the laser signal.

Surface Degradation

Facet Damage From Oxidation in Laser Diodes

Oxidation of a source facet can lead to slow degradation. Sources that contain higher concentrations of aluminum tend to inhibit the oxide growth. Alumium particles are active and inhibit diffusion to the facet by decreasing the junction temperature. AlGaAs/GaAs sources will develop oxide thickness proportional to their output power levels when operating at low power and will grow thickness proportional to the square of the output power levels when operating at higher power levels.

Catastrophic Optical Damage (COD)

COD occurs as a result of facet melting due to current concentration and optical absorption. Optical absorption that encourages nonradiative recombination results in heating and melting at the facet. The heat generated will also cause the bandgap to shrink and therefore as a result the current concentration increases creating more heat and the cycle continues.

The AlGaAs/GaAs sources are much more sensitive to this type of damage than the InGaAs(P)/InP sources. Where the first is considered unstable against oxidation and has high rates of facet oxidation, the second has a much lower rate of oxidation with respect to time and output power. The same is true for COD as the first will experience this at levels less than 1 MW/cm^2 the second will experience not until power densities of tens of MW/cm^2 have been reached. One solution to this is a non-absorbing mirror structure or NAM. The Japanese are working on fabricating this type of technology but it is difficult to manufacture at present.

Alloy Electrodes

In sources (and photodetectors) with alloy electrodes, there develops degradation as a result of the metal diffusing in towards the inner region. One example of an alloy type electrode is AuZnNi. During operation the metal will diffuse creating spikes along with the direction of current flow. The result is dark spot defects in the inner region of the semiconductor. The Schottky-type electrodes such as Ti/Pt/Au do not seem to cause the same degradation. The metal forms an inert interface with between the electrode and the semiconductor surface.

Bonding Parts

Soft-solders can reduce mechanical stresses on the bonding surface but tend to add to early degradation of the device. In, Sn, and Sn-rich Au-Sn are among the type of soft (low melting point) solders that are attributable to solder instabilities like whisker growth, thermal fatigue, void formation at the bonding part, and diffusion similar to what occurs with the alloy electrodes when in contact with the semiconductor surface. The instabilities directly lead to sudden premature failures. The higher melting point solders, or hard solders which include such materials as Au-rich AuSn eliminate many of the instabilities that plague devices that have problems with soft solders.

Buried Heterostructure

In Buried Heterstructure diodes (BH), the configuration and index of refraction changes nearby the active region of the laser diode creates a waveguide for light emerging from the interactions. This type of laser is considered an "index-guided" laser. The n-type InGaAsP active emitting region is surrounded on both sides by the p-type InP. The degradation mode in these lasers is associated with a breakdown or degradation of the active region due to a decrease in injected carriers. The degradation of the BH interface is considered a wear out failure and is not a sudden type failure.

Above is a summary of the most generally common characteristics and degradation modes of laser diodes and LEDs. Facet degradation is specific to laser diodes. Some degradation modes can be eliminated through redesign of the semiconductor structures or through packaging techniques. For more information please review the references at the end of this paper.

Reliability Equations:

There are several methods of extrapolating source lifetime including methods of calculating lifetime given power output operating temperature, device drive currents, and decrease in output power. Below are several of the exprapolation equations for predicting source lifetime.

Output Power:

The lifetime of a laser diode or LED can be approximated by the following relationship. Given an initial power output of the device P_o and the exponential lifetime τ, the power output over time t, can be extrapolated.

$$P_{out}(t) = P_o e^{-t/\tau} .$$

Assume that for a given time t, the power output of the device has dropped to a percentage from the initial power level such that Power ratio, $P_R = P_{out}/P_o$ and solve for t such that,

$$\tau = -t / \ln(P_R) .$$

Now with t known, as well as the initial power output P_o, the power output $P_{out}(t)$ can be extrapolated over time t.

Drive Current:

Another way of predicting source lifetime is by extrapolation of the current density. Elevated currents can bring out many of the degradation mechanisms associated with point defects in devices such as AlGaAs. If J is defined as the current density, the lifetime of the device is defined as t, and the empirical value parameter is defined as n, then there exists a relationship such that $t \propto J^{-n}$. Therefore if the lifetime of the device, t_o is known for a given operating current, I_o then a relationship between drive current and device lifetime can be deduced from

$$\frac{t_o}{t_2} = \frac{J_o^{-n}}{J_2^{-n}} = \left(\frac{J_o}{J_2}\right)^{-n} = \left(\frac{I_o}{I_2}\right)^{-n} .$$

Solving for t_2 such that a relationship exists where lifetime can be predicted as a result of elevated or decreased operating drive current, I_2.

$$t_2 = t_0\left(\frac{I_2}{I_0}\right)^{-n} .$$

The values of n range from 1.5 to 2.0, with the larger n indicating more of a reduction in operational lifetime or greater sensitivity of the device to increased currents.

Temperature:

For determining the relationship between temperature of the device to predict lifetime an Arrhenius relationship can be expressed as,

$$t = ce^{Ea/kT}$$

where

E_a is the activation energy for the device in units of eV,

k is Boltzman's constant = 1.38 * 10^{-23} Joules/Kelvin,

T is absolute temperature, (273.2 + °C) in units of Kelvin,

c is the device constant in units of time, and

e is electron charge = 1.6 * 10^{-19} joules/eV.

The lifetime in this relationship is defined as unexceptable drive currents for lasers where the drive currents elevate to 1.2 to 1.5 times the rated drive current and for LEDS can be output power loss below that of the rated value due to point defects. For life time versus temperature calculations the following E_a, activation energies can be used:

AlGaAs/GaAs lasers ~ .7 eV
AlGaAs LEDs ~.5 eV
InGaAsP/InP (longer wavelength) ~ .16 eV
InGaAsP/InP Buried Heterostructure ~ .9 eV
GaAlAs Double Heterstructure LED ~ .56 eV.

Given a known activation energy E_a, operating temperature T_o and lifetime of the device t_o, the constant can be calculated by

$$c = t_o e^{-Ea/kT_o} .$$

Or as a ratio, t_2 can be solved for in terms of T_2 given T_o and t_o such that

$$\frac{t_o}{t_2} = \frac{e^{Ea/kT_o}}{e^{Ea/kT_2}} .$$

Simplifying to solve for t_2 as a function of the temperature for accelerated life testing,

$$t_2 = t_o e^{-\frac{Ea}{k}\left[\frac{1}{T_o} - \frac{1}{T_2}\right]} .$$

Note that for photodetectors the degradation mechanisms are different but the same Arrhenius relationship can be used to determine lifetime of the device given different operating temperatures. The same relationship holds with the activation energy being ~ .7 eV for infrared detectors. Also it is important to note that the criteria for detector lifetime degradation is based on receiving an unacceptable signal to noise ratio output as a result of the accelerated temperature life test.

References

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