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Effects of Radiation on Laser Diodes

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Effects of Radiation on Laser Diodes

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Abstract

The effects of ionizing and neutron radiation on the characteristics and performance of laser diodes are reviewed, and the formation mechanisms for nonradiative recombination centers, the primary type of radiation damage in laser diodes, are discussed. Additional topics include the detrimental effects of aluminum in the active (lasing) volume, the transient effects of high-dose-rate pulses of ionizing radiation, and a summary of ways to improve the radiation hardness of laser diodes. Radiation effects on laser diodes emitting in the wavelength region around 808 nm are emphasized.

Acknowledgments

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Glossary

Active layer (also active region): the undoped volume of a diode laser in which carriers recombine radiatively to produce optical gain and photon emission.

ARROW: antiresonant reflective optical waveguide, a laser diode geometry in which a sequence of antiresonant Fabry-Perot resonators is constructed by using alternate layers with differing refractive indices. ARROWs allow spectrally broad operation and high fabrication tolerances.

Bar: a cleaved section of a wafer onto which the layers of a laser diode have been deposited. The industry standard for a laser diode "bar" is a 1-cm-long, incoherent linear array of individually emitting diodes. The resonator cavity length is typically between 600 μm and 1000 μm. Bars can be stacked to form a two-dimensional array.

Broad-area (also broad-stripe, broad-waveguide, wide-stripe): a term used to describe a laser diode having a stripe width of about 100 μm or larger and no lateral cavity definition.

Buried heterostructure: a laser structure combining the features of gain guiding and index guiding to produce confinement of current, photons, and carriers.

Characteristic temperature, T_0: a parameter characterizing the temperature dependence of the threshold current density. A lower T_0 corresponds to a more rapid increase in threshold current density with increasing heat sink temperature.

Characteristic temperature, T_1: a parameter characterizing the temperature dependence of the differential quantum efficiency. The higher the value of T_1, the less sensitive is η_D to temperature.

Cladding layers: Layers situated above and below the confinement layers and having energy band gaps greater than the energy band gaps of the confinement layers.

COD (also COMD): catastrophic optical (mirror) damage, the power limit in a laser diode at which sudden, irreversible failure of a facet occurs.

Confinement layers (also confining layers, waveguiding layers): the layers adjacent to the active region.

CW: continuous wave, an unpulsed operating mode of a laser.

Dark line defect: a mobile linear network of dislocation loops and dipoles that propagates in the active region of a laser diode, ultimately causing device failure.

Dark spot defect: a circular defect associated with the clustering of like atoms to form precipitates or droplets in the active region of a laser diode.

DBR: distributed Bragg reflector, a laser diode arrangement in which multilayered gratings are located on either side of the active region, rather than within it, as in a DFB.

DFB: distributed feedback, a non-Fabry-Perot type of laser diode in which light confinement is provided by a grating (periodic modulation of refractive index) that is incorporated into the active region. The grating selects a single lasing mode.

Differential quantum efficiency (also external efficiency, slope efficiency), η_D: the incremental increase in output power with forward current after the current threshold has been exceeded; the percent of injected carriers that are converted to laser light output. Units: W/A.

Double heterostructure (also double heterojunction): a laser diode design in which there is an active layer that is sandwiched between two confinement layers with higher band gaps.

Edge-emitting diode laser: a semiconducting laser that emits in the direction perpendicular to the direction of epitaxial growth. It produces elliptical beam cross sections and exhibits large beam divergence.

Fabry-Perot: a laser design in which a standing-wave pattern is produced in an optical cavity with mirrors at both ends. Edge-emitting diode lasers and VCSELs are Fabry-Perot, as opposed to DFB, devices.

Far-field pattern: the diffraction pattern of a laser diode observed at an infinite distance from the source.

Filamentation: a beam distortion caused by a nonlinear regenerative mechanism in which carrier density fluctuations lead to refractive index fluctuations and self-focusing of light in the active region of a broad-area laser diode. Oscillating fields and unstable far-field patterns result when the lateral mode profile is broken into multiple filaments. Beam filamentation can be suppressed by high-quality, uniform materials growth that minimizes the presence of defects and impurities.

Gain guided: a laser diode structure in which the lateral (horizontal) confinement of the light propagating through the active region is accomplished by the small refractive index variation produced by the current-generated population inversion. In the vertical direction, light is reflected back into the active region by the lower refractive indices of the confining layers.

GCSEL: grating-coupled surface-emitting laser, a grating-based semiconductor laser in which light is emitted from the surface, as in a VCSEL, but the light is propagated in-plane as in an edge-emitting design.

Gray (Gy): the SI unit of absorbed dose for nonparticle-based ionizing radiation. A gray is equivalent to the deposition of 1 joule of energy per kilogram of material. 1 Gy = 100 rad

GRINSCH: graded-index separate confinement heterostructure, a laser diode SCH structure in which the refractive index of the confinement layers is varied continuously rather than stepwise.

This allows optical confinement to occur separately from the carrier confinement caused by the difference in the energy band gap of the confinement layers.

Heterojunction: the area of contact between two layers that are made from different semiconductor materials.

High power: a term describing a laser diode whose output power is hundreds of mW.

Homojunction: the area of contact between two layers that are made from the same semiconductor material but differ in the type of doping.

Index guided (also buried heterostructure): a laser diode structure in which the active region is defined laterally (in the horizontal plane) by a material with a lower refractive index; this refractive-index step allows both carrier confinement and photon confinement. A ridge-waveguide laser is an exampled of an index guided structure.

Internal quantum efficiency (also internal efficiency), η_i: the percent of carriers injected into the active region that recombine radiatively, *i.e.*, produce photons.

LED: light emitting diode, a device resembling a laser diode that is operated below its threshold current.

Laser diode (also diode laser, injection laser, semiconductor laser): a laser in which stimulated emission is achieved by passing electrical current through a semiconductor p-n junction.

LOC: large optical cavity, a type of double heterojunction in which the effective optical width is increased by the use of confinement layers with the same refractive index as the active layer.

MBE: molecular beam epitaxy, a fabrication technique in which beams of atoms are directed toward a substrate to form successive monolayers.

Mesa: a ridged stripe structure defined by photolithographical etching down to a level below the active region.

MOCVD (also MOVPE, metal-organic vapor phase epitaxy): metal-organic chemical vapor deposition, an industrial fabrication technique in which alkyls and hydrides are reacted to form multilayer semiconductor devices.

MOPA: master oscillator power amplifier, a laser diode configuration in which a narrow, single-stripe DFB or DBR master oscillator is coupled to a power amplifier, which typically has a tapered-stripe design.

MQW: multiple quantum well

Near-field pattern: the diffraction pattern of a laser diode observed at a finite distance from the source.

QCW: quasi-continuous wave, an operating condition using relatively long pulses (*e.g.*, 500 μs) and low duty cycles to simulate CW operation while allowing thermal dissipation.

Quantum well: an active region that has been made thin enough that electron energy is quantized in the vertical direction. The thickness is typically 12 to 50 nm, which is comparable to the de Broglie wavelength of the electrons (about 10 nm).

Rad: a unit of absorbed dose for nonparticle-based ionizing radiation. A rad is equivalent to the deposition of 100 ergs of energy per gram of material. 1 rad = 1 centigray (cGy)

SCH: separate confinement heterostructure, a laser diode design in which the quantum well active layer is sandwiched between two confinement layers, beyond which are two cladding layers.

Single heterostructure (also single heterojunction): a laser diode design made from two different materials and containing both a homojunction and a heterojunction.

SQW: single quantum well

Strained layer: a layer in which tensile or compressive strain has been intentionally introduced so that certain material properties are attained.

Stripe geometry: a laser diode design in which the width of the active layer is no greater than 10 to 15 μm in order to confine current filamentation to a single "filament." The regions outside the stripes can be treated by proton bombardment or by oxide deposition.

Tapered-stripe (also flared amplifier): a laser diode design in which one facet is smaller than the other. A tapered stripe can be used as the power amplifier in a MOPA. Tapered-stripe geometries yield high beam quality and good efficiency, but their reliabilities tend to be lower than those of nontapered designs.

Threshold current: the lowest forward bias current at which lasing action takes place. Unit: A.

Threshold current density, J_{th}: the minimum areal current density which must be passed through the active region of the laser diode to cause onset of lasing action. Units: $A \cdot cm^{-2}$

VCSEL: vertical-cavity surface-emitting laser, a semiconductor laser that emits in the direction of epitaxial growth rather than from the edge, as conventional laser diodes do. VCSELs have symmetrical beam cross sections, small beam divergence, and smaller threshold currents than those of conventional laser diodes. However, the output power of VCSELs is relatively low.

Wall-plug efficiency (also power conversion efficiency), η_P: the percent of overall electrical power that is converted to optical power.

Introduction

A laser diode (also known as a diode laser, semiconductor laser, or injection laser) is a semiconductor in which stimulated emission occurs at the p-n junction when a forward bias is applied. Holes from the p-type material and electrons from the n-type material are driven to the junction, or active region, where they radiatively recombine to form photons. Because the active region is bounded by reflective facets, it constitutes a resonant optical cavity, and lasing occurs above a certain threshold current. High-power laser diodes can be used as pump sources for solid-state lasers. The most widely used solid-state laser material is neodymium-doped yttrium aluminum garnet (Nd:YAG), which emits at a wavelength of 1.06 μm. The maximum absorption intensity of the Nd^{3+} ions doped into the YAG crystal occurs at about 808 nm, so this is the optimum region for pumping. Laser diodes emitting in the vicinity of 808 nm will be emphasized in this report. For industrial applications, solid-state lasers are commonly pumped by flash lamps. Unfortunately, flash lamps emit broadband spectra that poorly match the narrow absorption lines of the dopant ions. The resulting inefficiency causes heating of the laser material, leading to decreased beam quality and output power. Typically, less than 3% of the electrical input power to flash lamp systems is converted into laser radiation.[1] Laser diodes, on the other hand, exhibit narrow spectral emissions; a diode-pumped Nd:YAG laser system has shown an optical-to-optical efficiency of 53% and an electrical-to-optical efficiency of 28%.[2] Moreover, the lifetimes of diode lasers (5000 to 10,000 hr) exceed those of flash lamps (less than 1000 hr).[3] Other advantages of high-power diode lasers as compared to flash lamps are the smaller size, the simpler power and cooling supplies (lower voltages), and the fact that the light from laser diodes is directional and can be focused to a small spot, thereby increasing the achievable pump intensity.[4]

Short History of Laser Diodes

The earliest laser diode designs (homojunctions, single heterostructure, double heterostructure) required high threshold currents and active cooling. As materials science capabilities advanced and allowed the controlled deposition of extremely thin semiconductor layers, the threshold currents decreased and the efficiency increased. High-power laser diodes of the 1980s typically employed multistripe arrays[5] to reduce the occurrence of beam filamentation effects. Generally, these were double-heterostructure devices composed of lasing stripes coherently coupled by evanescent field overlap. Since the 1990s, gain-guided broad-area designs based on separate-confinement heterostructure (SCH) quantum wells have become the standard layer structure for high-power laser diodes. Broad area designs increase the power level at which catastrophic optical damage occurs by reducing the peak optical power density at the mirror facet.[6]

The standard format for high-power laser diodes designed to pump solid-state lasers is a 1-cm-long monolithic array that can be stacked to create a two-dimensional emitting aperture.[7] These arrays can be used in either CW or quasi-CW (QCW) mode. In QCW operation, a series of long pulses is used to match the upper-state lifetime of the solid-state laser (a few hundred microseconds to a few milliseconds). It has been predicted[8] that a reliable 100-W CW laser bar will be available by 2006.

1962: First reports on semiconductor lasers based on p-n homojunctions.
1968: First laser-diode-pumped Nd:YAG laser.
1969: First room-temperature operation of single-heterostructure laser diodes.
1970: First major advance: Room-temperature operation of double heterostructure laser diodes made possible by improvements in liquid-phase epitaxy.
1973: First reports of separate-confinement double heterostructure laser diodes.
1977: First room-temperature operation of a quantum-well laser diode.
1980s: Progress in MBE and MOVPE facilitates the production of quantum-well lasers.
1982: First laser diode with a GRINSCH design.
Early 1990s: The power of 1 cm × 0.06 cm laser bars reaches more than 20 W, with a lifetime of 10,000 hr.
1991: First Al-free active-area laser diodes emitting in the 808-nm spectral region.

Effects of Aluminum on Laser Diodes

Laser diode failure can be attributed to three main mechanisms:[9]

(1) At high optical power densities (about 50-100% of the catastrophic optical damage level), degradation occurs by an optical process at the laser facets. The rate of degradation increases with optical power density.
(2) At optical power densities less than 50% of catastrophic optical damage limits, a gradual degradation mechanism caused by point defect generation (primarily at the laser facets) predominates. The defects are thought to derive from oxide surface states.
(3) A sudden failure mechanism characterized by dark-line defects (DLDs) is independent of optical power density. DLDs are propagating dislocation networks caused by nonradiative recombination of injected and/or photogenerated carriers. They arise from material defects such as localized impurities or from mechanically damaged areas in the lasing region.

The presence of aluminum in the active area of a laser diode can contribute to all three mechanisms. Due to the aluminum, AlGaAs quantum-well diode lasers have a shorter lifetime and an increased degradation rate as compared to GaAs lasers. In fact, the reliability of AlGaAs lasers has been a limiting factor in their use in a variety of systems. Part of this is due to the high susceptibility of aluminum-containing materials to oxidation. Since the addition of indium to the GaAs system eliminates the sudden failure mechanism (the large indium atoms pin dislocations that would otherwise propagate[10]) and slows the gradual degradation rate, quaternary InAlGaAs strained-layer materials tailored to operate at 0.81 μm have been developed. For a completely Al-free material at 0.81 μm, studies have focused on the InGaAsP system, which is unstrained. The temperature rise at the facets is much lower for lasers with InGaAsP active areas than it is for AlGaAs lasers.[11] Both the InAlGaAs (with more than ~5% In) and the InGaAsP lasers show the absence of sudden failures. The gradual degradation mechanism is also slowed in both these systems, as evidenced by the fact that they have a longer typical lifetime than that of AlGaAs lasers. Addition of Al into the active region causes a degradation of the device performance due to the introduction of centers for nonradiative recombination.[12] A comparison of laser diode materials emitting at 808 nm is shown in Table 1.

Table 1. Semiconductor laser diode active-layer materials for emission at 808 nm.

	Sudden Failure	Typical Lifetime	Power at which COD occurs
GaAs (~60 Å)	Yes	8000 h	11 MW/cm^2
AlGaAs	Yes	4000 h	
InAlGaAs	No	5000 h	
InGaAsP	No	>5000 h	~18 MW/cm^2

It should be noted that even though aluminum is detrimental in the active layer, a completely aluminum-free laser diode structure is not desirable. Laser diodes lacking Al in the waveguide layers or the cladding layers have small bandgap discontinuities which cause carrier leakage and lead to a high threshold-current density, J_{th}; low characteristic temperature of the threshold current, T_0; and low differential quantum efficiency, T_1. A high-band-gap cladding layer made from InAlGaP has been used by Coherent Inc.[13,14]

Radiation Overview

In terms of hazardous environments to which laser diodes could conceivably be exposed, radiation can be categorized into two types: ionizing and particle. The high-energy photons of gamma rays and X-rays are types of ionizing radiation, and energetic neutrons are examples of particle radiation. By and large, the main effect of ionizing radiation in materials is the production of electron-hole pairs, and the primary mechanism of particle radiation is atomic displacement. However, high-energy neutrons such as those produced by deuterium-tritium fusion (E = 14 MeV) can produce significant ionization in materials in addition to displacement.[15] The effects of protons and electrons are not considered in this report.

When ionizing radiation such as 1-MeV γ-rays from a ^{60}Co source interacts with a semiconductor, it mainly displaces bound electrons, thereby producing electron-hole pairs. These primary electrons move through the material and generate secondary (Compton) electron cascades. If dopant impurities are present in the material, the electrons or holes may be captured at the impurity atom sites, and recombination may not occur unless the material is annealed. These charged defect sites serve as nonradiative recombination centers during the operation of laser diodes. The energy required to generate an electron-hole pair in the semiconductor GaAs is about 4.8 eV, and about 7×10^{13} $pairs \cdot cm^{-3}$ are generated per rad (charge yield per unit dose).[15]

Neutrons are considerably more damaging than γ-rays because of their effectiveness in producing displacement defects. The simplest type of displacement damage is a Frenkel defect, which consists of the dislodged atom, referred to as an interstitial, and its empty lattice site, known as a vacancy. Complex defects (associations of radiation-induced defects with each other and with preexisting impurities or lattice defects) are generally stable at room temperature. The collision of a neutron with the lattice can transfer a large amount of energy to a primary knock-on atom, which in turn can cause a dense cascade of several hundred displacements.[16] This cluster of defects is thought to exist as a large disordered region with dimensions of a few hundred Ångstroms[15] and to contain a high density of nonradiative recombination sites.

Radiation-induced defects produce energy levels in the band gap and therefore affect the electrical properties of semiconductors. In general, irradiation of laser diodes speeds up aging characteristics, increases threshold current, shifts the lasing wavelength, produces mode structure changes, decreases light output at constant current, and increases turn-on time delays.[17]

The light output of a laser diode is directly related to the recombination rate or, alternatively, the lifetime of the excess minority carriers. If the light emission originates on the p-side of the laser diode junction, then the minority carriers are electrons. Lifetime damage can be described by

$$\frac{\tau_0}{\tau} = 1 + \tau_0 K \Phi , \qquad (1)$$

where τ_0 is the preirradiation value of the minority carrier lifetime, τ is the post-irradiation lifetime value, K is a damage constant in $cm^2 \cdot s^{-1}$, and Φ is the radiation fluence in cm^{-2}. Specifically, for neutron radiation the fluence units are $n \cdot cm^{-2}$, and for gamma radiation the units are $photons \cdot cm^{-2}$. (See the Appendix for the conversion between rads and $photons \cdot cm^{-2}$ for gamma radiation.) Because many laser diode operating parameters show a postirradiation change that is a function of $\tau_0 K \Phi$, the factor $\tau_0 K$ can be used as a measure of radiation sensitivity.[18] For example, the increase in the threshold current due to radiation is proportional to $\tau_0 K \Phi$.[18] The damage constant K, which is largely determined by the type of radiation and the material composition,[19] essentially gives the number of nonradiative centers introduced per unit fluence or dose of radiation per second.[18] Since the radiation hardness of different materials may be compared by calculating their $\tau_0 K$ values, the quantity $1/\tau_0 K$ can be interpreted as a threshold fluence at which a shift in threshold current becomes noticeable.[17]

Much of the available data on radiation effects in laser diodes (see Table 2) was obtained using older, low-power devices, but most of the general trends are also applicable to newer devices.

Effects of Gamma Irradiation on Laser Diodes

It was noted early on that for GaAs lasers the threshold current density J_{th} increased and the light intensity (measured below the threshold current) decreased with ^{60}Co gamma radiation dose.[20] Ionizing radiation leads to a reduction of the minority carrier lifetime due to an increase in the number of nonradiative recombination centers, which compete with radiative centers for excess carriers.[20,21] This means that the quantum efficiency η decreases, leading to the increase in the laser threshold current. Typical minority carrier lifetimes in GaAs laser diodes are a few nanoseconds operating with currents smaller than the threshold current (non-lasing, LED-type mode), and some picoseconds while operating under stimulated emission conditions. Therefore, the light output of the laser diode while lasing is nearly unaffected by radiation, because a much larger concentration of radiation-induced defects is required to influence the radiative recombination rate than under subthreshold conditions.[22]

In the case of high-power laser diode arrays, threshold current and differential quantum efficiency values are typically affected by less than 10% for doses up to 4 Mrad of ^{60}Co gamma rays. Also, spectral outputs and near-field patterns do not change significantly after irradiation.[23] (It has recently been reported that the spectral properties of a strained MQW InGaAlP laser diode emitting in the visible region did change noticeably after gamma irradiation.[24,25]) About a 10% loss in optical power was observed for modern InGaAsP laser diodes emitting at 1.3 μm after a room-temperature gamma dose of 10^3 rad.[26] Doses up to about 10^7-10^8 rad of γ-radiation do not cause catastrophic failure of laser diodes,[17] and laser diodes which are designed for high power and high speed (for use in data transmission lines) show only small reductions of light output power up to ^{60}Co gamma doses of 10^8 rad.[22]

The ionizing-radiation-induced recombination sites have relatively low activation energies, and their effect on J_{th} can be reversed by thermal annealing or by forward-biasing the diodes, as in the lasing condition. Annealing also occurs over time at room temperature. When high-power IR laser diodes were exposed to gamma radiation while being operated CW at their maximum rated powers, the laser intensities degraded slightly and the far-field beam patterns showed small changes in ellipticity. Partial recovery of intensity occurred after 1 h, and full intensity was regained after several days. After at least two days of recovery, there was no observable change in J_{th} or in external quantum efficiency. Beam ellipticity returned to the pre-irradiation value after 1 h, but the major and minor axes were smaller.[27] If gamma-irradiation is carried out at elevated temperatures, thermal annealing of the radiation damage takes place simultaneously with defect generation, which reduces the degree of device degradation. For example, in the InGaAsP laser diodes mentioned above, there was no degradation in optical power when irradiation occurred at 200°C.[26]

Semiconductors undergo transient photocurrents from intense gamma-ray pulses from nuclear weapons (typically 10^6 to 10^{12} rad(Si)·s^{-1} for a duration of less than 1 ms).[28] The electron-hole pair concentrations generated by a pulse with a dose rate of 10^9 rad(Si)·s^{-1} are as high as 10^{18} cm^{-3}, well above most semiconductor doping levels. Even though this process would tend to produce a positive photocurrent in the laser cavity, the effect of a simultaneous radiation-induced reduction of the resistivity of the confinement regions is larger and leads to a net decrease in current density, due to carrier leakage from the active volume.[29,30] The higher the dose rate, the larger the resistivity decrease in the confinement areas.[31] At a critical ionizing irradiation (from electron beams rather than gamma rays) dose rate of about 10^{11} to 10^{12} rad(Si)·s^{-1}, the net current density of a laser diode decreases to J_{th}, and lasing is temporarily interrupted.[29,32] After the end of the radiation pulse, lasing resumes; the optical power at first overshoots its original level, then experiences relaxation oscillations before steady-state operation is restored. These results agree with the effects observed for pulsed X-rays (see below). At a dose rate of about 10^{10} rad(Si)·s^{-1}, there is also a small shift in the emission spectrum toward shorter wavelengths.[29]

It may be mentioned here that visible and infrared laser irradiation has been used for many years to simulate the transient effects of radiation pulses on semiconductors. In fact, the first such study,[33] which appeared in 1965, was performed at Sandia. There have been several recent reports[30,31,34,35] on the application of this technique to the testing of laser diodes emitting at 1300 nm.

In summary, gamma irradiation is unlikely to cause significant degradation of performance in laser diodes at room temperature.[23] While the lasers are operating with high current densities and short minority carrier lifetimes, they are relatively insensitive to ionizing radiation.

Effects of Neutron Irradiation on Laser Diodes

Lattice damage in the form of displacements is significant in its effect on laser diode operation. These defects cause local perturbations in the energy levels and create additional nonradiative recombination centers. Other possible effects of lattice damage include changes in index of refraction, increased absorption or scattering, and changes in electrical properties such as carrier lifetime, electrical resistance, and carrier mobility.[36] The values of the damage constant K (and therefore of $\tau_0 K$) are approximately 100 times greater for neutron irradiation damage than for that caused by gamma irradiation.[37]

Since the nonradiative recombination sites compete with the radiative recombination process, neutron irradiation increases the threshold current at which lasing occurs.[38,39] In the relatively simple GaAs-based single-stripe lasers, the increase in threshold current started to become significant at fluence levels of about 10^{13} to 10^{14} $n \cdot cm^{-2}$,[23] and fluences up to about 10^{14} $n \cdot cm^{-2}$ did not cause catastrophic failure.[17] For high-power laser diode arrays, no change was detectable in J_{th} up to 9.9×10^{12} $n \cdot cm^{-2}$, but by 9.1×10^{13} $n \cdot cm^{-2}$, the threshold current had increased by about 40%. Therefore, it appears that neutrons affect high-power laser diodes to about the same degree as the older single-stripe laser diodes.[23] The increase in J_{th} is primarily caused by a decrease in internal quantum efficiency η_i. The quantum efficiency is reduced by an increase in the concentration of deep levels which act as nonradiative recombination centers. Even though neutron irradiation increases J_{th}, it does not significantly alter the spatial distribution of the emitted light pattern.[40] Therefore, neutron-induced defects apparently are distributed relatively uniformly, as would be expected for a primary knock-on mechanism.

The neutron-induced increase in threshold current is greater at higher temperatures. Since lasers with large pre-irradiation temperature sensitivity also exhibit greater radiation sensitivity, this correlation can be used to predict radiation-dependent performance if the temperature dependence is known.[41] Also, the parallel between reduced temperature sensitivity and less susceptibility to radiation damage suggests that continued improvement in laser diode operating characteristics will be accompanied by improvement in radiation hardness.[19]

Neutron bombardment also reduces the light output of laser diodes due to permanent radiation-induced lattice damage.[19] However, at operating currents well above J_{th}, the decrease is relatively insensitive to dose.[18] This is because of the very short radiative lifetimes (about 10^{-11} s) during intense laser operation. The degradation in light output, like the increase in J_{th}, results from the generation of nonradiative recombination centers (or centers that radiate at a different wavelength) that compete with the usual radiative centers lying close to the valence band.[17] It does not appear that neutron irradiation produces significant losses from light scattering or light absorption due to color centers in the active region.[40] Neutron irradiation of bulk GaAs can lead to induced optical absorption, but no appreciable change occurs at wavelengths near the band edge unless the sample has received high doses.[17]

Various other effects resulting from neutron bombardment include the following: Neutron irradiation appears to increase the susceptibility of the laser diode to facet damage.[38,42] In certain laser diodes, a blue shift of the lasing wavelength has been observed after neutron irradiation.[43] Also, the anode-cathode voltage for a given current is slightly reduced after neutron irradiation.[44]

Little thermal annealing occurs below 300 K in neutron-irradiated GaAs.[40] Annealing of neutron damage in laser diodes requires temperatures of at least 125-150°C.[45] Some forward-bias annealing of neutron-induced damage does occur when the lasers are operated after irradiation, and significant recovery can be induced in a neutron-irradiated laser diode by application of a short burst of relatively high current.[41] Partial annealing takes places during lasing because the high density of minority carriers fills or otherwise deactivates some of the nonradiative traps.[39] It should be noted that forward-bias annealing in CW mode at high currents can cause increased heating, both internally and at junction and contact points,[38,42,46] and J_{th} increases with increasing temperature.[39,47] In the case of high neutron fluences ($\sim 10^{15}$ $n \cdot cm^{-2}$), heating effects caused by CW operation can lead to "thermal rollover," in which the output power reaches an upper limit and begins to decrease as the current is increased.

There is apparently no information that has been published in the scientific literature regarding the real-time effects of neutron irradiation on laser diodes while they are operating. An unpublished study that was performed at Sandia's Annular Core Research Reactor (ACRR) in 2000 by Dan Rey *et al.* indicated that there was a substantial increase in J_{th} when a single-stripe, fiber-coupled laser diode manufactured by Coherent Inc. was subjected to a neutron pulse with a large fluence of 1.0×10^{14} $n \cdot cm^{-2}$ while being operated in a quasi-continuous-wave mode.[48] The radiation effects annealed to some degree as lasing continued, but even after 10 minutes, the value of J_{th} was still about 90% higher than it was before the neutron pulse. Figure 1 shows the results of this test, which used a 1.6-Watt, model F-81-1600C laser diode emitting at 810 nm. (For comparison, Fig. 2 shows the effects of neutrons from the Sandia Pulsed Reactor III on the same type of device, but in this case the irradiations were carried out while the diode was not lasing.) A similar, 0.8-Watt F-81-800C Coherent laser diode operated at 1.25 A showed a large decrease of about 50% in optical output as a result of a neutron pulse from the ACRR. These results are shown in Fig. 3. It would be helpful to see more studies performed during neutron irradiation, especially if they explored the effects as a function of dose.

Effects of X-Rays on Laser Diodes

A nuclear event produces X-rays in addition to γ-rays and fast neutrons. In fact, under high-altitude or exoatmospheric conditions, the majority of the energy is given off as X-rays.[28] If an electronic system survives the initial burst of thermal X-rays, then it is subjected to the effects of prompt X-rays.[17] Therefore, the response of operating lasers at very high prompt X-ray dose rates is of interest.[49] A high-power multistripe laser diode array and a broad-area laser diode that were tested in a flash X-ray simulator showed only slight perturbations of their outputs when subjected to radiation pulses at dose rates up to 10^{11} rad·s^{-1}. (A different publication confirms that there is no influence on laser diodes from pulsed X-ray irradiation up to 10^{10} rad·s^{-1}.[50]) However, significant effects were observed at dose rates near 10^{12} rad·s^{-1}. When run CW at rated output power, the laser diodes exhibited a 500-μs interruption of current and laser output in response to the radiation pulse. After the optical power recovered from the pulse, it oscillated above and below its initial value. The laser diodes also exhibited temporary turn-on effects from the off state. At dose rates near 10^{12} rad·s^{-1}, they turned on for as long as 20 μs with up to twice the rated laser output when exposed to the radiation pulse.[23,42] When increased shielding and shorter cables were used in the experiment, the transient turn-on and turn-off effects were either greatly reduced or eliminated, depending on the laser diode. Therefore, the X-ray effects were attributed to electromagnetic pulse (EMP) or photoinduced currents on the cables to the laser diodes. Careful design of the electronic system is necessary to avoid problems with high-power diode lasers in severe prompt X-ray environments.

Improving the Radiation Hardness of Laser Diodes

Some desirable characteristics of a laser diode for operation in a radiation environment include the following: 1) low threshold current so that the difference between J_{th} and the maximum operating current is large, 2) optimum heat sinking to increase the maximum operating current, 3) minimal dependence on temperature, 4) low minority carrier lifetime, 5) high radiance, and 6) high initial light output.[18,51] It has been theoretically predicted that changes in cavity length can affect the radiation resistance of laser diodes, but there is a tradeoff between radiation hardness and optoelectronic device performance.[52]

It has been reported that vertical cavity surface-emitting lasers (VCSELs) show excellent resistance to a variety of radiation conditions.[53,54] However, a recent Sandia report concluded that a GaAs-based VCSEL emitting at 850 nm underwent a 30% decrease in output power after being exposed to a fluence of 4.4×10^{13} n·cm^{-2} from a fission neutron source.[55] Since VCSELs have several advantages in comparison to conventional edge-emitting laser diodes, including better output beam characteristics such as circular cross section and low divergence, low threshold currents, and high-temperature operation, they merit consideration for use in potential optoelectronic applications. VCSELs are still in development and at present do not produce powers as high as those with edge-emitting designs.[45] In the future, however, they could become the dominant type of laser diodes.[56]

Recently, it has been reported that quantum dot semiconductor lasers show enhanced radiation hardness as compared with edge-emitting quantum well lasers.[57-59] Because this technology is very new,[60] little information is available. However, quantum dot laser diodes have exhibited very low threshold current densities, and the spatial localization of carriers prevents their nonradiative recombination at the cavity mirrors, thereby avoiding overheating.[61] The use of quantum dots in laser diodes is one of the goals of the Defense Advanced Research Projects Agency's Super High Efficiency Diode Sources program.[62]

Monitor Diodes

It should be noted that many high-power laser diode systems use internally integrated monitor diodes as part of a feedback circuit to control operating conditions so that the laser diode provides a constant optical power level.[45] In such cases, the radiation degradation of the embedded photodiode that is monitoring current and light output is an important consideration, because the monitor diode degrades separately from and often more severely than the laser diode itself. Radiation-induced degradation of the monitor diode could cause the feedback circuit to overdrive the laser into catastrophic failure.[42] Also, even though laser diodes undergo injection-enhanced annealing, monitor diode degradation does not anneal.[45]

Summary Points

- In general, gamma irradiation of laser diodes is not a particularly important problem. The more significant consideration for most laser diodes is sensitivity to neutron irradiation, which is about 100 times more damaging.
- The presence of aluminum in the active area of a laser diode reduces device reliability, but the use of aluminum in the confinement and/or cladding layers is desirable.
- The major effect of irradiation on laser diodes is the increase in threshold current density, J_{th}, through the creation of nonradiative recombination centers that compete with radiative recombination sites.
- Gamma irradiation does not cause major problems at doses lower than 10^7-10^8 rads, especially if the irradiation is carried out under lasing conditions.
- Annealing of gamma radiation effects occurs 1) over time at room temperature, 2) at elevated temperatures, and 3) in response to lasing.
- Very high dose rates of ionizing radiation (10^{11}-10^{12} rad·s^{-1}) can adversely affect the electrical properties of laser diodes. These effects can be mitigated by the use of shielding.
- Neutron irradiation causes significant damage in laser diodes at doses higher than 10^{13}-10^{14} n·cm^{-2}.
- Partial annealing of neutron damage can be achieved by operating in lasing mode after irradiation. Thermal annealing occurs at moderately elevated temperatures.
- In order to minimize radiation effects, a laser diode should have a low threshold current and a very high maximum operating current.[63]
- It is not expected that the newer types of high-power laser diodes will be more susceptible to radiation damage than the older designs. In fact, the trend toward the development of commercially desirable operating parameters such as lower threshold currents and improved cooling characteristics generally contributes to increased radiation hardness.
- Vertical-cavity surface-emitting lasers have the potential to become the next generation of high-power laser diodes, and they show good resistance to radiation. Progress in VCSEL development should be monitored, especially since Sandia is the source of some of the leading research in the field.

Table 2. Summary of radiation data for laser diodes.

Type of LD	Mfr.	Max. Output Power	Type of Radiation	$\tau_0 K$ (cm^2)	Dose Rate	Fluence	% Incr. in J_{th}	Notes	Yr.	Ref.
Zn-diffused	IBM		Neutron	3.2×10^{-15}		1.8×10^{15} n·cm^{-2}	N/A	Operated below J_{th}	1971	64
Low-power, homojunction	RCA		Gamma	1.7×10^{-17}	0.7 Mrad/h	5.0×10^{7} rad	N/A	Operated below J_{th}	1970	20
Low-power, homojunction	RCA		Neutron	$1.3\text{-}11 \times 10^{-15}$		2.6×10^{14} n·cm^{-2}	300	Operated near J_{th}	1971	37
Single heterojunction	RCA		Neutron	8×10^{-15}		3.2×10^{14} n·cm^{-2}	300		1974	17,65
Single heterojunction	LDL		Neutron			4.0×10^{13} n·cm^{-2}	97		1982	51
Stripe, double heterojunction	LDL	14 mW	Gamma	$.06\text{-}2.0 \times 10^{-17}$		1×10^{8} rad(Si)			1980	36
Stripe, double heterojunction	LDL	14 mW	Neutron	5×10^{-15}		5.8×10^{13} n·cm^{-2}	40		1980	17,36, 51
Stripe, double heterojunction	RCA*	15 mW	Gamma	$1.5\text{-}7.1 \times 10^{-17}$		1×10^{8} rad(Si)			1980	36
Stripe, double heterojunction	RCA	15 mW	Neutron	6×10^{-15}		5.8×10^{13} n·cm^{-2}	18		1980	17,36, 51
GaAs double heterojunction	M/A-COM	1.5 W	Neutron			2.3×10^{14} n·cm^{-2}	~100		1984	41
Single spatial mode GaAlAs	RCA	5 mW	Neutron			2.0×10^{14} n·cm^{-2}	31		1984	41
Multistripe, MQW	SDL	200 mW	Gamma		0.410 Mrad(Si)/h	4×10^{6} rad(Si)	0	Decrease in efficiency	1989	23,42
Multistripe, MQW	SDL	200 mW	Neutron			9.1×10^{13} n·cm^{-2}	36		1989	23
Multistripe, MQW	SDL	200 mW	Neutron			1.2×10^{15} n·cm^{-2}	150		1989	38,42

Multistripe, MQW	SDL	500 mW	Neutron			1.2×10^{15} n·cm^{-2}	240	CW operation	1989	42
Ten-stripe, MQW Array	SDL	2 W	Neutron			1.2×10^{15} n·cm^{-2}	175	Stopped lasing at this fluence in CW	1989	38,42
Broad-area, SQW	McDD		Gamma		0.279 Mrad(Si)/h	4×10^{6} rad(Si)	7	No change in efficiency	1989	23
Broad-area, SQW	McDD		Neutron			1.2×10^{15} n·cm^{-2}	614		1989	38
Single-stripe, CSP	Hitachi		Neutron			2.5×10^{14} n·cm^{-2}	86		1990	66
Single-stripe, SQW	SDL		Neutron			2.5×10^{14} n·cm^{-2}	100		1990	66
Ten-stripe, [MQW?]	SDL		Neutron			3.0×10^{14} n·cm^{-2}	290	Large decrease in efficiency	1990	66
Heterojunction			Gamma		$2.5\text{-}3.1\times 10^{4}$ rad(Si)/h	900 rad(Si)	62		1992	67
InGaAsP	Philips	1 mW	Gamma		$0.2\text{-}6 \times 10^{5}$ rad(Si)/h	5×10^{7} rad(Si)		780 nm	1992	21,50
InGaAsP	Philips	1 mW	Neutron			1.15×10^{13} n·cm^{-2}		780 nm	1992	21,50
Single-stripe, SQW	SDL		Neutron			1×10^{14} n·cm^{-2}	~100		1994	44
AlGaAs double heterojunction	Mitsubishi	60 mW	Gamma		0.45 Mrad(Si)/h	1×10^{6} rad(Si)	0	Irradiated while lasing CW	1996	27
Single-stripe, fiber-coupled	Coherent	1.6 W	Neutron			1.1×10^{14} n·cm^{-2}	68	Sandia Pulsed Reactor III	1999	48
MQW InGaAlP	Samsung		Gamma			2.4×10^{6} rad		Decr. effcy. & diff. spectrum (672 nm)	2002	24,25
AlGaAs double heterojunction		5 mW	Gamma		0.3 Mrad/h	9×10^{6} rad	5		2003	68

*The properties of this particular laser diode were unusually sensitive to γ-radiation.[36]

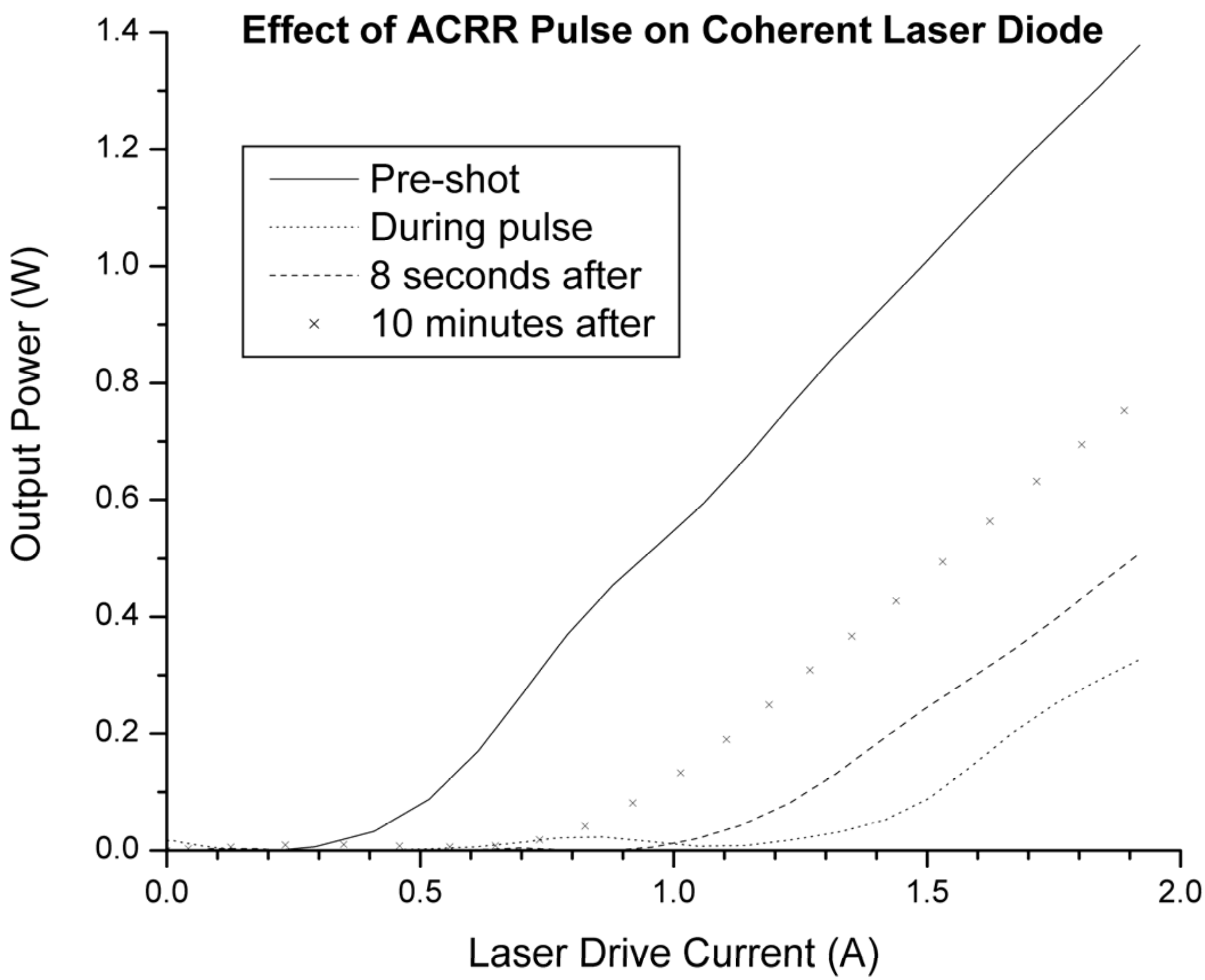

Figure 1. Effects of neutron irradiation on an operating Coherent Inc. laser diode during and after the pulse.

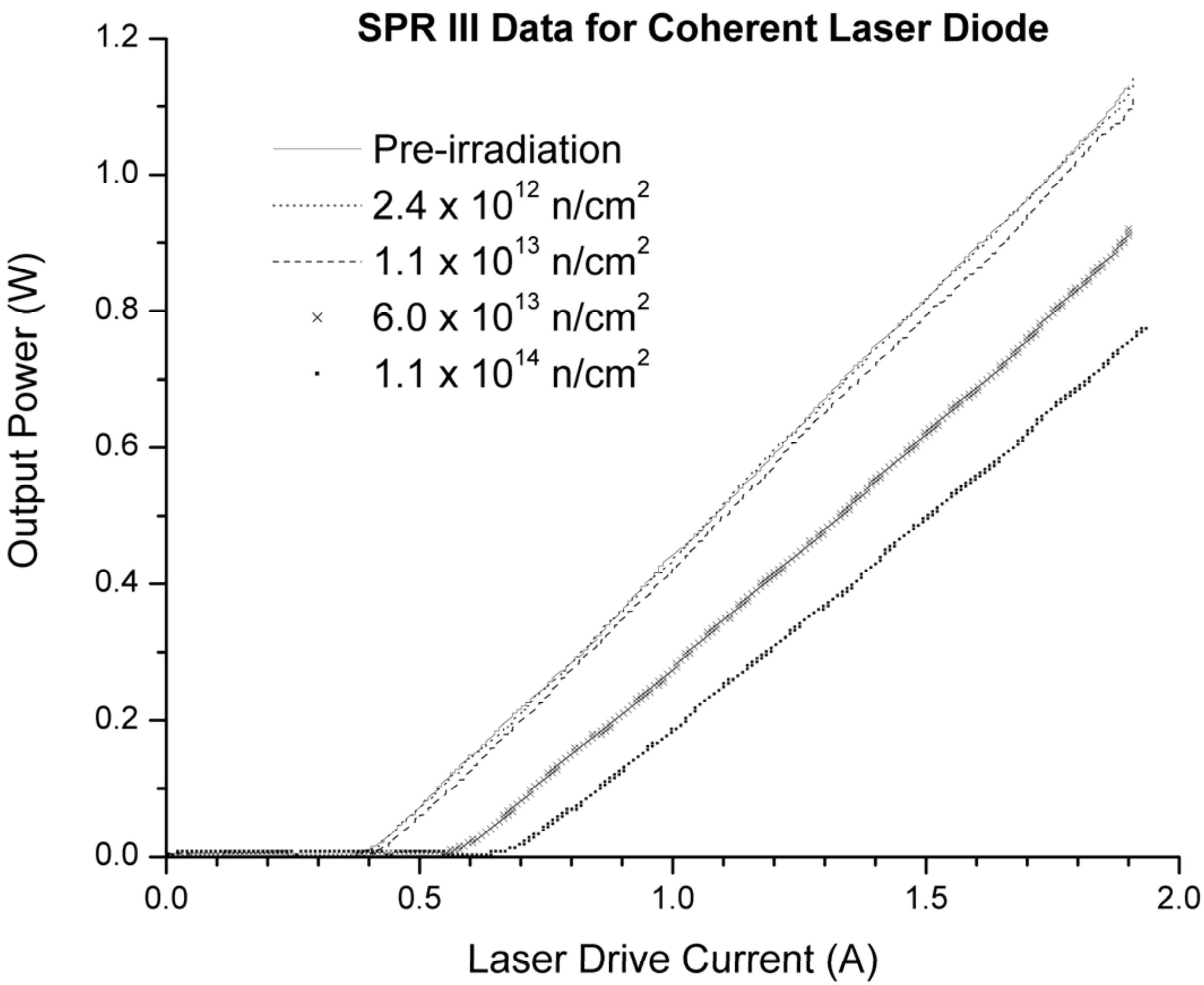

Figure 2. Effects of successive neutron irradiations on a Coherent Inc. laser diode.

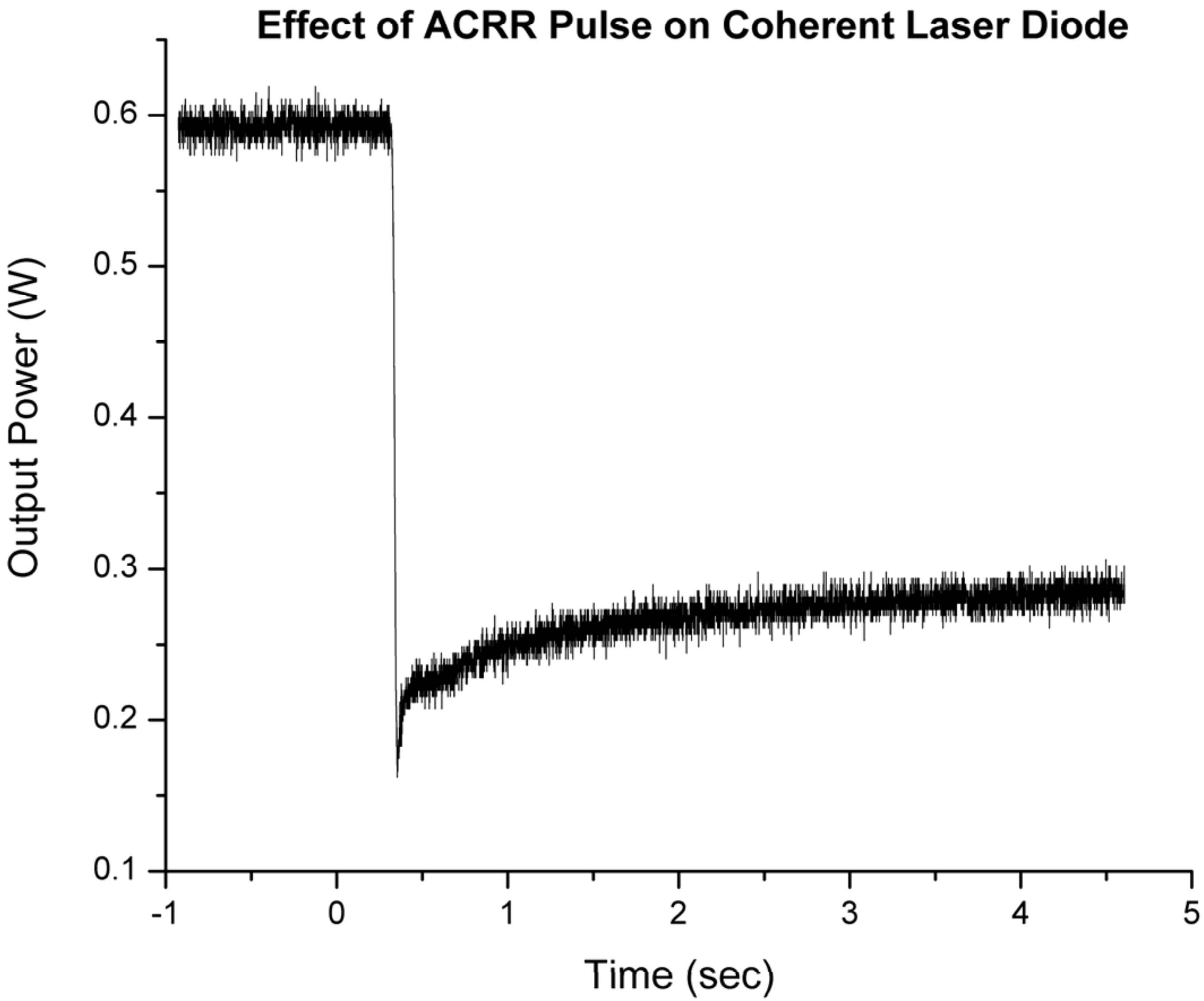

Figure 3. Drop in optical power exhibited by an operating Coherent Inc. laser diode when subjected to a neutron pulse.

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Appendix

Conversion between cm^2 and rad^{-1} units for $\tau_0 K$:

1 roentgen (R) of 1-MeV photons = 1.95×10^9 photons·cm^{-2}.

This fluence of 1-MeV photons deposits an absorbed dose of 0.865 rad in silicon.

Since 1.95×10^9 photons·cm^{-2} = 0.865 rad(Si), the factor for converting from $rad(Si)^{-1}$ to cm^2 is 4.44×10^{-10} rad(Si)·cm^2.

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