ELECTRON IRRADIATION OF GaAsP LEDs

Kathryn Conway Dimiduk, Christian Quarles Ness
and James Kevin Foley
Physics Department
Naval Postgraduate School, Monterey, CA 93943

ABSTRACT

Five different compositions of epitaxial GaAsP and GaP LEDs were irradiated with 30 MeV electrons to fluences of 10^{14} electrons/cm². Light output during irradiation and current-voltage characteristics before and after irradiation were measured. Damage coefficients were determined to be 2×10^{-13} cm²/electron for GaP and approximately 3×10^{-14} cm²/electron for GaAs_{1-x}P_x compositions $x = .3 - .9$. At 300K partial annealing occurred in seconds. Transmission losses through the LED lens and epoxy cap due to irradiation were measured and found to be insignificant below 10^{15} electrons/cm² at 30 MeV. Compared to earlier GaP and GaAsP LEDs measured at lower electron energies, these LEDs were significantly less radiation tolerant. Several possible explanations are suggested.

INTRODUCTION

The purpose of the experiments reported here was to measure the effects of electron irradiation on commercially available LEDs. GaAsP and GaP LEDs were chosen as these LEDs have many applications in displays, as opto-couplers or opto-isolators, and as transmitters for fiber optic systems. While other workers have reported electron radiation damage on GaAsP and GaP LEDs, their work is primarily from 1965-1970 [1-7]. It was felt that improvements in device technology warranted a new study of these devices.

Five compositions of LEDs were irradiated with 30 MeV electrons. The specific LED parameters studied were light output, current-voltage characteristics, and lens and epoxy transmission. This data was then used to compute a damage coefficient (according to the method of Rose and Barnes, [8]) for each LED composition. These damage coefficients were compared for composition dependence and compared with earlier work in the literature on similar LEDs.

EXPERIMENTAL

Five different compositions of GaAsP and GaP LEDs were studied. All of these LEDs were fabricated by Hewlett Packard Electrooptics Division of Palo Alto, CA. Specific compositions, growth methods, substrates, and LED wavelengths are listed in Table 1. The LEDs were all made using standard production line chips (see [9 or 10] part numbers 1N5765, 1N6092, 1N6093, 1N6094, HEMT 6000, HEDS 5000, HEDS 6000 for additional information) but were specially mounted in a TO-46 can without a lens or epoxy cap. This meant the electron beam would not have to pass through a lens or epoxy layer before striking the semiconductor chip. Thus any possibility of dose build-up due to electron induced Bremsstrahlung photons in the lens or epoxy was avoided. It has been suggested that this precaution was unnecessary and experiments are underway to verify this. Lenses and epoxy disks were irradiated separately and transmission losses were measured using a Perkin-Elmer 330 spectrophotometer.

Table 1. Composition, wavelength and growth information on LEDs studied. (LPE = liquid phase epitaxy, VPE = vapor phase epitaxy, i=indirect gap, d = direct gap).

LED Material	Growth Method	Substrate	Lattice Mismatch	E _g	Wavelength (nm)
GaP	LPE	GaP	no	i	560
GaAs _{0.1} P _{0.9}	VPE	GaAs	yes	i	580
GaAs _{0.35} P _{0.65}	VPE	GaAs	yes	i	635
GaAs _{0.6} P _{0.4}	VPE	GaAs	yes	d	655
GaAs _{0.7} P _{0.3}	VPE	GaAs	yes	d	705

All irradiations were done at the Naval Postgraduate School Linear Accelerator (LINAC). The irradiations used $30 \pm 1/2\%$ MeV electrons in a pulse train. The individual pulses were 10^{-6} s long and had a repetition rate of 60/s. The electron current was monitored with a secondary emission monitor (SEM) and integrated. Beam area was determined using a scanning wire probe connected to a Beckman current integrator. Typically, average flux rates were 10^{12} electron/cm²-s. Total fluences were 10^{12} to 10^{14} electrons/cm². The conversion to Rads depends on stopping power which in turn depends on mass. Since copper has the closest mass to Ga and As of the elements tabulated in [11], Rad (Cu) was chosen as being closest to Rad (GaAs). The conversion factor to Rad(Cu) is estimated to be 3×10^7 (electrons/cm²)/Rad(Cu) resulting in approximate doses of 3×10^4 to 3×10^6 Rad(Cu). All samples were at room temperature during irradiation.

Figure 1 shows the configuration of the LINAC target chamber during LED irradiation. The LEDs were angled approximately 15° with respect to the electron beam and aimed at a photodetector. The LEDs were powered during irradiation (constant current or constant voltage as indicated in the data). The

Figure 1. Configuration of the LINAC target chamber during LED irradiation.

photodetector output was connected to the y axis of an xy recorder. A time base was used for the x axis, resulting in a plot of light output versus time that could be converted to light output versus dose. At specified times (dose levels) irradiation was stopped. Light output was then observed to partially recover for the next approximately 30 seconds. After this annealing, current-voltage characteristics were measured and irradiation was continued. This was repeated at intervals until the desired final cumulative dose was reached. Data was taken on twenty-one LEDs from seven wafers. Fig. 3 in the data and analysis section will show the variability between LEDs from the same wafer.

DAMAGE COEFFICIENT THEORY

One standard way to summarize radiation damage to an LED is to use a damage coefficient. This technique is explained and the equations derived by Rose and Barnes [8] for neutron irradiation of LEDs. Additional information is given in a review by Barnes [7]. This theory is applied to electron irradiation with damage coefficients given in terms of $\text{cm}^2/\text{electron}$ instead of $\text{cm}^2/\text{neutron}$. The pertinent equations are summarized below.

The carrier lifetime after irradiation, τ , can be written in terms of the initial carrier lifetime, τ_0 , the electron fluence Φ , and a damage coefficient, K , as in Eq. 1.

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

The damage coefficient, $K = \sigma_{NR} v_{th} C_1$ where C_1 is the probability per electron of creating a nonradiative center, v_{th} is the thermal velocity, and σ_{NR} is the cross section of the created nonradiative center.

Equation 1 can be used directly in terms of lifetimes. Alternatively, equations 2, 3 & 4 can be used to rewrite Eq. 1 in terms of more easily measured parameters: light output, L , current density, J , and voltage, V .

$$L = C_2 \tau \exp(qV/kT) \quad (2)$$

$$J = C_3 / \sqrt{\tau} \exp(qV/kT) \quad (3)$$

$$J = C_5 / \tau \exp(qV/2kT) \quad (4)$$

C_2 , C_3 , and C_5 are constants, k is Boltzman's constant, and q is the charge of an electron. Eq. 2 applies if the light output (which is proportional to radiative current) is diffusion controlled. Equations 3 and 4 for current density (proportional to current for constant area devices) apply respectively to diffusion or space charge controlled current.

The current or light output control mechanisms are determined by plotting $\log J$ or $\log L$ versus V and examining the slope. Requiring experimental conditions of constant current or constant voltage and knowing whether L and J are diffusion or space charge controlled, one can use Eq. 1-4 to derive the equations in Table 2 that relate light output or total current density to the damage coefficient K for the specified conditions. The damage coefficients reported in this paper were all determined from the equations of Table 2.

Table 2. Equations for determining the damage coefficients in terms of the light output, L , and the current density, J . Quantities with and without subscripts 0 refer to before and after irradiation respectively. D refers to diffusion controlled and sc to space charge control. J or V are listed under exp't depending on which must be held constant during measurements.

Equation	Requirements	
	L and/or J	Exp't
$[(\frac{L_0}{L})^{2/3} - 1] = \tau_0 K \Phi$	L: D J: D	J
$[(\frac{L_0}{L})^{1/3} - 1] = \tau_0 K \Phi$	L: D J: SC	J
$[(\frac{J}{J_0}) - 1] = \tau_0 K \Phi$	L: SC J: SC	J
$[(\frac{L}{L_0}) - 1] = \tau_0 K \Phi$	L: D	V

DATA AND ANALYSIS

Light output versus time during irradiation was measured for each LED. Figure 2 shows an example of this for a typical $\text{GaAs}_{.35}\text{P}_{.65}$ LED. (Similar measurements were made for each composition and the results are discussed below). This irradiation was done in four steps, stopping after each step to observe annealing and measure current voltage characteristics. The solid lines are during irradiation and the solid lines with dots are with the beam off. The curve for each subsequent irradiation has been shifted back in time to overlap the previous irradiation curve. During each irradiation the light output drops. It then recovers some of this loss in about twenty seconds after the beam is stopped, as indicated by the dotted portion of the lines.

Figure 2. Light output (normalized to initial light output) as a function of time for four consecutive irradiations of one $\text{GaAs}_{.35}\text{P}_{.65}$ LED. (—) during irradiation (10^{12} electrons/ $\text{cm}^2\text{-sec}$), (—•—) following irradiation (room temperature annealing). Each irradiation followed the previous anneal but has been shifted back in time to overlap the previous irradiation.

Figure 3. Light output of LED normalized to initial light output ($L/L_0 \times 100$) versus cumulative electron fluence. Points were read off curves such as in Fig. 2 which were obtained with the LEDs powered in either a constant current (open symbols or x) or constant voltage (closed symbols) mode.

Measurements as described above were made on twenty-one different LEDs, three each from seven different wafers. Figure 3 (above) compares the results from these LEDs. Twelve were run at constant current and nine at constant voltage. An idea of the variation between devices can be seen by comparing the LEDs of the same composition: approximately a factor of 2 variation in electron flux required to reach a given degradation for the constant current devices and a considerably larger variation amongst the constant voltage devices.

Consider first the constant current data in Fig. 3. The GaP points are all somewhat lower than the GaAsP points and define their own line. The various compositions of GaAsP do not show a consistent pattern of degradation versus composition; The scatter pattern of points of the same composition is as large as that between the different compositions. Thus one line is drawn for all three GaAsP compositions. For the constant voltage points there is too much scatter to be able to draw a good line through the data. One is drawn to aid the eye but should not be considered a fit to the points.

The devices powered at constant current appear softer than the ones powered at constant voltage. This is to be expected because the damage mechanism is the creation of nonradiative centers which contribute to the total current but not the light output, essentially a parasitic current. Thus in a constant current mode, where the total current is fixed, as the nonradiative current becomes a larger fraction of the total, the radiative current must decrease. In the case of constant voltage, the current is allowed to increase to cover the additional pathway. The difference in composition is not thought to be as significant as the method of powering the devices as will be discussed later.

Before irradiation and after each stage in a successive irradiation, as in Fig. 2, current-voltage characteristics were measured. Fig. 4 shows the data for three GaAs_{0.7}P_{0.3} LEDs from the same wafer for an irradiation with 8×10^{13} electron/cm². The slope of the curves indicates these LEDs had diffusion controlled total current both before and after irradiation. Note that for a given voltage the total current increases with increasing radiation dose as explained above. The spread in the data is indicated by comparing the three before and three after curves. The relative behavior of each device is similar.

Figure 4. Current versus voltage characteristics of 3 GaAs_{0.7}P_{0.3} LEDs (---) before irradiation and (···) after irradiation with 8×10^{13} electrons/cm².

Fig. 5 shows similar data for one GaAs_{0.1}P_{0.9} LED. For this figure, current-voltage data are shown before irradiation and after four successive irradiations. Unlike in Fig. 4, the current-voltage curves do not maintain the same curvature before and after irradiation and therefore leading to intersect. These two figures were chosen because they indicate the range of behavior observed. It was generally noted that LEDs of the same composition showed the same type of curves while the shapes of the curve and the crossing or lack thereof varied with composition.

Figure 5. Current versus voltage characteristics of one GaAs.₁P.₉ LED, (□) before irradiation, (o) after irradiation with 10^{12} electrons/cm², (Δ) after irradiation with 10^{13} electrons/cm², (+) after irradiation with 5×10^{13} electrons/cm², and (x) after irradiation with 10^{14} electrons/cm².

From curves such as those in Fig. 4 and 5 the total current was determined to be diffusion or space charge controlled by measuring the slope of the I-V curves. The control mechanism for the radiative current was found from similar curves of light output versus voltage. This information was then matched with the equations in Table 2 to determine the lifetime damage coefficient product. The values for LEDs of each composition were averaged. Table 3 lists these results. A larger lifetime damage coefficient product indicates less radiation tolerance. Comparing these numbers indicates that GaP is softer than GaAsP. Also, as in the light output data, there is not a significant trend of lifetime damage coefficient product with composition for GaAsP.

Table 3. Lifetime damage coefficient products for five LED compositions. Experimental conditions and current control mechanisms used to determine these constants are given. (L = light output, (current control mechanism of radiative current); J = total current density, (current control mechanism of total current); SC = space charge controlled; and Diff = diffusion controlled).

LED Material	Exp't Condition	Control Mechanism	$\tau_0 \times K$ (10^{-13} cm ² /e)
GaP		L: SC	2.
		J: SC	
GaAs. ₁ P. ₉		L: SC	0.6
	constant	J: SC	
GaAs. ₃₅ P. ₆₅	current	L: Diff	0.2
		J: SC	
GaAs. ₆ P. ₄		L: Diff	0.4
		J: Diff	
GaAs. ₇ P. ₃	constant voltage	L: Diff	0.2

Light transmission through glass lenses and through red and green epoxy disks (made from epoxy cap material) was measured before and after irradiation. Measurements were made as a function of wavelength and are shown in Fig. 6 and 7 for a fluence of 10^{15} electrons/cm². Lower fluences did not show significant changes in transmission. The transmission of the glass lenses was found to be rotation sensitive so care was taken to use the same orientation before and after irradiation.

Figure 6. Light transmission of glass lens versus wavelength, (—) before and (---) after irradiation with 10^{15} electrons/cm².

Figure 7. Light transmission of epoxy cap versus wavelength, (—) before and (---) after irradiation with 10^{15} electrons/cm².

Light output as a function of wavelength was also measured before and after irradiation for the various compositions of LEDs. A modified Beckman DK-1A spectrophotometer was used for these measurements. No change was observed to within the resolution of the instrument, 3-5 nm.

Additional figures and data on individual devices is included in [12, 13]. The data presented in this section is summary of the work in these two theses.

COMPARISON WITH OTHER ELECTRON IRRADIATION EXPERIMENTS

Several authors have reported electron damage studies of GaAsP, GaP and GaAs LEDs. Millea and Aukerman [1, 2] report a damage coefficient of 2×10^{-15} cm²/electron for GaAs LEDs. This is an order of magnitude harder than our GaAsP LEDs and two orders of

magnitude harder than our GaP LEDs. Stanley [1] obtained a damage coefficient for epitaxial GaAs ($1-2 \times 10^{-13}$ cm²/e), for diffused GaAs ($1.2-1.5 \times 10^{-14}$ cm²/e) and for GaP (4×10^{-15} cm²/e). Our GaP value is two orders of magnitude softer than his. Our GaAsP value matches Stanley's diffused GaAs value though his Fig. 2 indicates GaAsP was somewhat harder than GaP. In addition, Stanley measured the transmission spectra of glass lenses and epoxy caps. Comparing this data indicates that our lens and epoxy are harder than his. Schade, Nuese and Herrick [4, 5] measured electron degradation of GaAsP LEDs as a method to determine trap levels. We were not able to measure the location of our traps to compare with the levels they reported. Schade et al. reported using a fluence of 10^{17} electrons/cm² to achieve orders of magnitude degradation. This cannot be directly compared with the results reported here or the other authors listed above. This information is summarized in Table 4. Barnes [6] and Barnes and Wiczer [7] summarize radiation damage in LEDs due to neutrons, gamma rays, and electrons. For electron irradiation of GaAsP and GaP LEDs they summarize the results of the above authors.

From Table 4 it is apparent that the various electron irradiation experiments have been done at different energies. Thus one must consider the effects of energy dependence of the damage mechanism. Table 5 lists various energy dependence data.

Table 4. Comparison of lifetime damage constant products from experiments on electron irradiation of LEDs.

Material	e Beam energy	τ_0 K or observation	Year	Ref.
GaAs	2 MeV	2×10^{-15} cm ² /e	1964	1
Epitaxial GaAs	2 or	$1-2 \times 10^{-13}$ cm ² /e	1970	3
Diffused GaAs	2.5 Mev	$1.2-1.5 \times 10^{-14}$		
GaP		4×10^{-15}		
GaAsP	1 MeV	10^{17} e/cm ² causes orders of magnitude degradation	1970	4
GaP GaAsP	30 MeV	2×10^{-13} cm ² /e 3×10^{-14}	1985	this work

Table 5. Energy dependence of various effects of electron irradiation.

Material	Parameter	Increase for 2 MeV $\rightarrow$ 30 MeV	Reference
n type Si	lifetime damage constant	x3	14
p type Si	lifetime damage constant	x13	14
n type GaAs	carrier removal rate	X3	15
	relative damage (displacement damage)	x2-3	15
	1/mobility	x30	15
copper	collision damage (displacement damage for thin samples)	x1.2	11

The data in Table 5 does not directly answer the question of the energy dependence of GaAsP and GaP LEDs. Ideally this should be measured experimentally. If one assumes that n type GaAs carrier removal or relative damage data is relevant, since the LED current is primarily carried by electrons, then our damage coefficients should be a factor of three larger than those measured at 2 MeV. The observed difference is considerably larger than this and still must be explained. If one chooses mobility data then the differences are explained in terms of energy dependence.

DISCUSSION

Light output versus electron flux was shown in Fig. 3 for GaP and for four compositions of GaAsP LEDs. The three compositions of GaAsP powered at constant current all decayed similarly with electron flux, to within the scatter in the data for a given composition. The GaP data had a similar amount of scatter but the average values were all shifted to lower fluence levels than the average values for each GaAsP composition. Thus it is concluded that within the accuracy of our data we do not see a difference depending on GaAsP composition, but that GaP LEDs are less radiation tolerant than GaAsP LEDs. The last GaAsP composition was powered at constant voltage and thus cannot be directly compared with the constant current data. This constant voltage data had considerably more scatter in light output versus electron flux than the constant current data did.

Two examples of current versus voltage data were shown, indicating the range of behavior seen. From this data, and from similar light output versus voltage data, lifetime damage constant products were calculated. Here all four GaAsP compositions and GaP can be compared. Values between GaAsP LEDs from the same wafer, between wafers and between constant current or constant voltage measurements were all similar. The GaP value LEDs were softer by an order of magnitude. Figure 8 plots lifetime damage constant products versus composition for $x = .3$ to $x = 1.0$.

Figure 8. Lifetime damage constant product versus composition

Epstein et al. [16, 17] have investigated gamma and neutron irradiation of GaAsP LEDs as a function of composition. They report a parabolic dependence on composition where pure GaAsP and pure GaP are significantly softer than the intermediate compounds. As can be seen in Fig. 8, our data could be consistent with a parabolic dependence on composition but without an $x = 0$ point as Epstein et al. had, we do not feel justified choosing a specific functional dependence on x . Thus we only report our data as one value for GaAsP and one for GaP, which differ by nearly an order of magnitude.

Because of the similar damage coefficients even between GaAsP wafers of differing composition it is felt that the difference between our results and the earlier results is significant and not just due to the use of a small sample size. As discussed in the previous section, at least part of this difference (at least a factor of 3) is due to the difference in measurement energies. Both the remaining difference and the difference between GaAsP and GaP can be explained with the same hypothesis; the lifetime damage coefficient product depends on crystal quality. From Table 1 it is seen that the GaAsP LEDs were grown on GaAs substrates where there is a lattice mismatch between the two materials and thus crystal strain where as the GaP LEDs were grown on GaP. In Stanley's work, [3], he cites differences in crystal quality in comparing his epitaxial GaAs and his diffused GaAs LEDs. All of our LEDs were epitaxially grown which gives better crystal quality, with GaP better than GaAsP due to the absence of a lattice mismatch. Barnes (Ref. 6) has also stated "The radiation hardness of these devices is inversely proportional to their purity and quality". Dose enhancement in Stanley's devices due to his having the lenses and caps on the LEDs does not explain the difference; it would give a correction factor in the wrong direction. Partial annealing of the LEDs was observed at room temperature in the first thirty seconds after radiation exposure was stopped. Further work needs to be done to establish the temperature dependence of this effect and the related time constants. Annealing also needs to be considered in deciding when to take post-irradiation data.

Comparing the fluence levels necessary to cause increased transmission losses in the glass lenses and the epoxy caps with the fluences necessary to cause device degradation, indicates that for constant current operation induced transmission loss effects are insignificant. For constant voltage operation the case is not as clear, in part due to the scatter in the constant voltage data. It appears that losses could be important if one wants to continue to operate the LED below about 40% of the initial light output.

CONCLUSIONS

GaAsP and GaP LEDs have been irradiated with 30 MeV electrons and the resulting device degradation has been measured. The four compositions of GaAsP studied behaved similarly while the GaP devices were somewhat softer. In constant current operation GaP and GaAsP LEDs were reduced to about 50% light output at fluences of about 10^{13} electrons/cm². At constant voltage operation at 10^{13} electrons/cm² GaAsP LEDs were only reduced to about 70% - 90% of their initial light output. Especially in the constant voltage data there was considerable variation between devices. Lifetime damage coefficient products were 2×10^{-13} cm²/electron for GaP and 3×10^{-14} cm²/electron for GaAsP. These values indicate less radiation tolerance than has been reported in the literature for previous GaP and GaAsP LED experiments measured at 2 MeV. At least part of this difference is due to the difference in electron irradiation energies. Part of the difference may also be due to better crystal quality in current LEDs. Partial annealing of the irradiated LEDs was observed at room temperature. Increased transmission losses in the glass lens and the epoxy caps due to electron irradiation was not found to be significant until fluences well above where the LEDs were seriously degraded in the constant current mode. In the constant voltage mode transmission losses could become important.

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