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TEMPERATURE AND CURRENT DEPENDENCE OF DEGRADATION IN RED-EMITTING-ETC(U)
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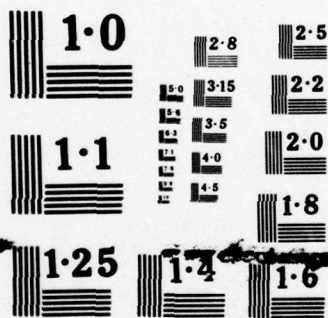
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10 J. M. Ralston J. W. Mann

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TEMPERATURE AND CURRENT DEPENDENCE OF
DEGRADATION IN RED-EMITTING GaP LEDs

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ABSTRACT

Experimental studies have been performed on several aspects of the degradation of electroluminescent quantum efficiency in Zn,O-doped GaP light emitting diodes. The dependence of degradation on stress temperature, stress current (experienced during accelerated aging) and measurement current (at which quantum efficiency is evaluated) has been empirically determined from experiments on several lots of devices. It is shown that degradation is dominated by a decrease in bulk p-side radiative recombination efficiency. The degradation of other factors (such as injection efficiency and injection ratio) contributing to the overall electroluminescent efficiency has only a secondary effect. Moreover, it is shown empirically that the dependences of degradation on temperature and stress current are separable.

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I. INTRODUCTION

In an earlier paper,¹ evidence was presented that a mode of bulk radiative efficiency degradation is operative in red-emitting LED material. This paper is concerned with characterizing the temperature and current dependence of red LED degradation. The diodes studies were fabricated from several different GaP slices: RP 55-35, RP 77-68, RP 71-38, RP 71-33, RP 71-39, RP 78-29 and RP 64-30.

In terms of degradation phenomenology, this study revealed that: 1. Degradation results primarily from a reduction in bulk radiative recombination efficiency on the p-side of the junction.¹ 2. Degradation of the net efficiency of thermally injecting minority electrons into the p-region, although sometimes appreciable, is not the dominant cause of LED failure. 3. The temperature and current dependences of degradation are separable. These observations are of considerable theoretical interest as well as a practical importance in predicting the reliability of devices incorporating these LEDs. A theoretical model of LED degradation based on early results of these experiments has been developed and presented earlier.²

II. EXPERIMENTAL PROCEDURES

The test devices were .015 in (0.4 mm) LED chips thermo-compression (TC) bonded p-up and hermetically sealed (in N_2 - He_2 ambient) in T0-18 glass-window packages. These devices exhibited a high order of reproducibility from device to device within a given slice batch. Any diodes notably different from the mean of the set in any characteristic

were culled before experimentation began. The most frequent cause of culling was an excess of nondiffusion current components at low bias (1.4V). Diodes were also occasionally eliminated from consideration due to excessive contact resistance.

Aging studies were most often performed at dc stress currents of 30 mA (20 A/cm^2). To obtain severe degradation within a reasonable time scale it was necessary to perform stressed aging at elevated temperatures. Obtaining data at too high a temperature, however, decreases the confidence of the results when extrapolated to practical device operating conditions. As a compromise, ambient stress temperatures of 100°C , 150°C and 200°C were chosen. The junction temperatures of the devices being stressed at 30 mA were $\sim 20^\circ\text{C}$ above ambient due to diode and header thermal resistance ($R_{\theta_{JA}} \approx 250^\circ\text{C/Watt}$).³

The devices tested were characterized first before degradation, again after the first hour of stress and subsequently at appropriate intervals thereafter. In most cases, this characterization consisted of measuring the external electroluminescent efficiency at (pulsed) measurement currents in the range 1-100 mA.⁴ As is shown later, measurement of device efficiency over such a wide current range is necessary to an understanding of the physical processes active in degradation and their influence on overall radiative recombination efficiency. These measurements are made rapidly and accurately using automated data acquisition and computer data storage. It is important to clearly distinguish this variable pulsed measurement current, used as a probe of degraded device performance, from the constant stress current applied continuously during elevated temperature aging which controls the rate at which the physical process of degradation proceeds.

In addition to the above standard measurements of quantum efficiency, detailed measurements of diode current-voltage (I-V) and light-voltage (L-V) characteristics were made, in specific cases, during degradation to study particular aspects of the degradation process, i.e., the fact that bulk degradation exists and the influence of nondiffusion current components.

III. EXPERIMENTAL RESULTS

In figure 1 is plotted (linearly) the ratio of degraded to initial efficiency (η/η_0) as a function of time (log scale). With the exception of slice RP 64-30, these devices are well grouped at all three temperatures used for accelerated aging. Generally, for diodes stressed at 30 mA in 200°C ambient and measured at 10 mA, η/η_0 is down to the range 0.70-0.75 after the first hour of aging. Among the samples studied, RP 55-35 is typical in its degradation behavior. The radically different behavior of slide RP 64-30 is an indication that its degradation causes may be different from those in general evidence.

As expected for processes which are thermally activated, degree of degradation is a monotonically increasing function of temperature, illustrated in figure 2. These data are shown on a scale of $\log \eta/\eta_0$ vs. root time stressed. Eckton⁵ has shown that this scale often has the effect of linearizing at least a portion of the degradation curve. Such linear regions, which may be used to define time constants, τ , are indicated in the figure. Also obtainable from such plots are the mean times to failure (MTTF) at the stated temperatures, defined to

be the time such that the group mean of $\eta/\eta_0 = 0.5$. In extrapolating high temperature stressed ageing data to operating conditions, under the assumption of an Arrhenius activation law, both MTF and τ have been used, with generally consistent results. This will be treated further in section IV.

Another important aspect of the degradation process is the dependence of relative degradation on measurement current (as opposed to stress current). Figure 3 shows that η/η_0 at a fixed time is a monotonically increasing function of measurement current. This effect cannot be explained by changes in injection efficiency between 2 and 100 mA (see section V) and requires a careful reconsideration of radiative recombination kinetics^{2,6,7} as related to device degradation.

The effect of varying stress current at a fixed ambient temperature and fixed measurement current is shown in figure 4. As might be initially expected, increased stress current enhances the degradation process. Because of thermal dissipation in the diodes under stress, junction temperature is necessarily higher at higher stress currents. Once an activation energy is obtained for the overall degradation process, the data can be corrected for this temperature dependence. This analysis is reserved to section IV, where it will be shown that an approximate power-law relationship holds between stress current and rate of degradation.

Although measurements of the degradation of electroluminescent efficiency reflect the most serious aspect of this problem from the standpoint of device reliability, there are other electrical measurements which can yield qualitative and quantitative information on physical degradation mechanisms. The most straightforward of these is the measurement of device current and light output at fixed voltage bias.⁸ Such an L-I-V plot, taken

on one typical diode, is shown in figure 5 before and after severe degradation. The light output at fixed voltage will be shown in section V to be independent of all current components except electron injection. The strong degradation in light output at fixed voltage will be shown to be unequivocal evidence that bulk radiative recombinations efficiency is being directly affected. At 1.4V the device current is virtually completely nondiffusion in origin. After degradation, on this particular device, $I(1.4V)$ has more than doubled. Yet the total current at 1.6V, still dominated by nondiffusion components, has not significantly increased. The current dependence of quantum efficiency, for the same diode, is shown in figure 6. The undegraded device exhibits a well-defined peak at ~ 3.5 mA, since injection efficiency increases with total current while bulk recombination efficiency decreases due to saturation of the radiative recombination centers. In the heavily degraded diode, such a peak is barely evident.

The time dependence of the relative light output at fixed voltage is of considerable importance, since it reflect directly the evolution of the process responsible for bulk p-side degradation. This is shown in figure 7 for the different samples under two different stress conditions. RP 55-35 and RP 78-29 were stressed at 30 mA at $T_{junc} \cong 220^{\circ}C$, while RP 71-39 was placed in a $250^{\circ}C$ ambient at zero bias. Both biased samples are reduced to $L/L_0 = 0.75$ after the first hour of stress. It will be shown that this "rapid" component of degradation is not a surface effect, but in fact represents bulk material damage. By contrast, the unbiased sample does not begin to show comparable degradation until well over 1,000 hours at $T_{junc} = 250^{\circ}C$ have elapsed. These data suggest that although these unbiased red LEDs do eventually exhibit measurable degradation at very high temperature, this process is strongly retarded in the absence of forward bias.

The same L-I-V measurements show the increase in nondiffusion current components as ageing progresses. Figure 8 shows the total device current (measured at 1.4V) of the same devices shown in figure 7. Here the marked difference in behavior between RP 55-35 and RP 78-29 is noteworthy. The former shows considerable fluctuation in current followed by a strong increase beginning at about 50 hours stress, while the excess current of RP 78-29 is steady, and begins to show a slow increase at about the same time. The unbiased sample, RP 71-39, stored at 250°C shows no significant increase in excess current components after almost 2,000 hours. Note that over the useful life of the current-stressed devices (less than 100 hours at these temperatures) the increase in excess current is in all cases negligible.

IV. TEMPERATURE AND CURRENT DEPENDENCE OF DEGRADATION

The generally accepted purpose of performing evaluated temperature degradation studies, as described above, is to come to some reasonable estimate of the useful life of the device under its expected operating conditions. To this end, the accepted practice has been to verify that the temperature dependence of the degradation process under a given combination of stress and measurement currents is reasonably described by Arrhenius' law:

$$t(T) = c \cdot \exp^{(E_A/kT)} \quad (1)$$

Here t is some suitably defined characteristic time of the degradation process at absolute temperature T , E_A is an apparent activation energy which describes the temperature dependence of degradation and c a properly dimensioned constant of proportionality. Once this law has been verified to an acceptable degree over the elevated temperature range studies, the constants c and E_A are used to extrapolate the process down to operating temperatures.

Obviously, the definition of the characteristic time used in equation 1 is a critical point. One convenient choice is the mean time to failure (MTTF): the time at which the average relative efficiency ($\langle \eta/\eta_0 \rangle$) of the sample group has dropped to a value of 0.5. Such a definition, by its very objectivity, effectively ignores all the structure observable in the time dependence of η/η_0 , and heavily weighs the first measurement of device efficiency and the measurements bracketing the $\eta/\eta_0 = 0.5$ point, ignoring all others. If more than one physical process is at work in the degradation process, this definition offers no hope of distinguishing them.

An alternate definition of characteristic time takes advantage of the linear regions observed when $\log \eta/\eta_0$ is plotted as a function of $\sqrt{\text{time}}$. (Cf. figure 2). The lines defined by these linear regions do not, in general, pass through the point $\eta/\eta_0 = 1$ at $t = 0$. This offset, which varies from slice to slice, is termed the "rapid component" of degradation, as distinguished from the "long term" linear region. The squared value of the exponential root-time constant describing the linear region is denoted τ . This choice of time parameter is particularly useful, since it may be measured when a group of devices is not sufficiently degraded to allow the measurement of a MTTF.

Since the MTTF is the parameter of interest in device operating life, its use is generally preferred as long as its temperature dependence satisfies equation 1. Figure 9 compares the results of using both MTTF and τ as characteristic degradation times. The diodes studies were stressed at 30 mA and measured at both 30 and 10 mA with results as shown. The MTTF values

are much less than the corresponding values of τ . This can be partly understood by noting that (in the absence of any rapid component of degradation) if the time dependence of degradation is ideally described by

$$\eta/\eta_0 = \exp(-\sqrt{t/\tau}) \quad (2)$$

then $\eta/\eta_0 = 0.5$ corresponds to $t \approx \tau/2$. The fact that MTF (at these temperatures, at this stress current) is generally less than half the corresponding value of τ reflects the presence of the rapid component of initial decay, which influences MTF but does not enter into the measurement of τ .

Figure 9 shows that both τ and the MTF, as measured on RP 55-35 in these experiments, agree satisfactorily with equation 1. As expected from figure 3, both MTF and τ are larger when η/η_0 is measured at 30 mA rather than 10 mA. Although the change in E_A between the two measurement conditions is not large, E_A generally tends to be slightly smaller for higher values of measurement current.

Figures 10 and 11 are Arrhenius plots of MTF versus junction temperature for diodes made from three slices of LED material. Figure 10 is data measured at 10 mA (where device parameters are often specified) and figure 11 is data measured at the 30 mA stress current. Both figures indicate that RP 55-35 and RP 71-38 are closely matched in failure characteristics, while RP 77-68 is measurably different. The fact that the thermal activation line of this last sample crosses those of the others may indicate the presence of a qualitatively different mechanism operative in its degradation.

The dependence of LED degradation on stress current (cf. figure 4) is a matter of considerable interest in defining practical operating limits. To determine this dependence, seven groups (10 each) of diodes from slice RP 55-35 were put on test at different combinations of stress current and ambient temperature. These results are shown in figure 12. The amount of degradation achieved is less than 50% for the 5 mA stress sample in the 100°C oven. Consequently, in figure 12 the long-term degradation time constant, τ , has been plotted as the characteristic degradation time, rather than the MTF. The consequences of this choice of time parameter may be inferred by reference to figure 9. That is, neglecting any initial degradation components, τ is approximately twice the expected MTF. The values of η/η_0 used to determine τ were obtained at 10 mA measurement current in all cases. Figure 12 indicates that while the overall time scale (c in equation 1) of degradation is strongly dependent on stress current, the activation energy, E_A , describing its temperature dependence, is not. As implied in the figure, an activation energy of 0.7 eV will be assumed valid for the 10 mA stressed data near 150°C. Using this value of E_A , equation 1 may be used to correct the measured characteristic degradation times to a junction temperature of 150°C. This data is plotted in figure 13, using both τ (open symbols) and MTF (solid symbols) as characteristic degradation times. When quantum efficiency is measured at 10 mA, the characteristic degradation times (MTF and τ) show an approximate inverse relation with stress current:

$$t = (\text{const}) \cdot I_{\text{stress}}^{-x} \quad (3)$$

with $x = 1.13$ for MTF and 0.83 for τ . This difference probably results from the arbitrary nature of the choices of characteristic degradation time,

since both MTTF and τ are obtained from data on the same degraded samples, which can experience only one history of damage, regardless of the method chosen to analyze it.

In practical device applications the "measurement" and "stress" LED currents are effectively the same. Figure 14 shows the dependence of MTTF on stress current when the quantum efficiency is measured at the same current at which the diodes have been stressed. This current dependence is shown for diodes placed in 150°C and 200°C ambients. An E_A of 0.7 eV has been used to correct the observed MTTF to a junction temperature of 150°C or 200°C. This current dependence is well described by $x = 0.56$ at both temperatures.

V. ANALYSIS AND DISCUSSION

In analyzing the degradation of Zn,O-doped GaP LEDs, it is useful to factor the external electroluminescent efficiency into several components:

$$\eta(I) = \eta_B \cdot f(I_e) \cdot R \cdot \eta_{inj}(I) \cdot \eta_{oc} \quad (4)$$

Here I is the total device current. η_B is the bulk electroluminescent efficiency at low-injection level and $f(I_e)$ is the factor that accounts for the saturation^{6,7} of Zn,O centers at higher levels of electron diffusion current, I_e . R is the ratio of electron diffusion current, I_e , to the total diffusion current, $I_e + I_h$. $\eta_{inj}(I)$ is the ratio of total (hole and electron) diffusion current ($I_e + I_h$) to total device current, I . (Previous authors^{6,7} have referred to the product $R \cdot \eta_{inj}(I)$ as "injection efficiency" but the present notation lends itself to a clearer analysis of degradation phenomena). Finally, η_{oc} is the efficiency of extracting an electroluminescent photon from the LED

chip, and should be of the order of 50%-60% (in plastic encapsulation).⁹ Although any of the factors in equation 3 can contribute to device degradation, the dominant loss will be shown to be from the $\eta_B f(I_e)$ product.

The optical coupling efficiency, η_{oc} , is chiefly dependent on chip geometry, refractive index of the encapsulant, surface roughness and contact absorbance. None of these have been shown to vary with degradation.

The injection ratio, R, for abrupt p-n junctions, is given by⁸

$$R = \left(1 + \frac{D_h}{D_e} \cdot \frac{N_A}{N_D} \cdot \frac{L_e}{L_h} \right)^{-1} \quad (5)$$

where D and L are the diffusion coefficients and diffusion lengths of minority carriers and N_A and N_D are the net acceptor and donor concentrations. Capacitance measurements after degradation reveal no detectable changes in the doping densities N_A , N_D . If the minority diffusion coefficients (or their ratio) do not vary, the injection ratio depends solely on the ratio of minority diffusion lengths.

These diffusion lengths have been measured¹ by SEM for several well-characterized typical samples (RP 55-35) after 1,500 hours of degradation at 220°C. Based on averages of ~10 measurements before and after degradation at distances of ~2 μm from the pn junction, the undegraded diodes show average diffusion lengths $\langle L_{eo} \rangle = 0.85 \mu\text{m}$ and $\langle L_{ho} \rangle = 0.36 \mu\text{m}$. The degraded values are $\langle L_e \rangle = 0.42$ and $\langle L_h \rangle = 0.22$. These values may be substituted into equation 5 to obtain the injection ratios before and after degradation, R_o and R:

$$R/R_0 = \frac{\left(1 + \frac{D_h}{D_e} \frac{N_A}{N_D} \frac{L_{eo}}{L_{ho}}\right)}{\left(1 + \frac{D_h}{D_e} \frac{N_A}{N_D} \frac{L_e}{L_h}\right)} = \frac{0.71}{0.67} = 1.07 \quad (6)$$

Where values^{8,10} of $N_D = 1.1E18\text{cm}^{-3}$, $N_A = 3.4E17\text{cm}^{-3}$, $D_e = 4.1\text{cm}^2/\text{sec}$ and $D_h = 2.8\text{cm}^2/\text{sec}$ have been used and assumed unchanged with degradation. The electroluminescent efficiency of the same diodes had been reduced to $\eta/\eta_0 = 0.1$, measured at mA. Therefore the change in injection ratio, R , although appreciable, is not a major factor. Interestingly, it appears that injection ratio can be enhanced in the course of overall degradation. As discussed in reference 1, it is not possible to make diffusion length measurements in the immediate vicinity of the junction. The measurements were therefore made a distance of a few diffusion lengths from the junction.

At this point, R and η_{oc} can be fairly eliminated as major factors in LED degradation. The remaining factors are $\eta_B f(I_e)$, the modulated bulk efficiency, and η_{inj} , the ratio of diffusion to total current. It is possible to measure the low level bulk efficiency variation directly by measuring the change in light output, L , at a fixed voltage bias chosen to be low enough that series resistance effects in the LED and saturation of the Zn,O centers are negligible. Under these conditions one has

$$L = \eta_B I_e = \eta_B \frac{q\sqrt{D_e} n_i^2}{N_A \sqrt{\tau_e}} \exp (qV/kT), \quad (7)$$

where n_i is the intrinsic carrier concentration, and τ_e the minority electron lifetime. It can be shown^{2,11} that at low levels of electron injection the degradation of bulk efficiency η_B/η_{B0} , equals the degradation of minority electron lifetime τ_e/τ_{e0} . One has then

$$\frac{\eta_B}{\eta_{B0}} = \frac{\tau_e}{\tau_{e0}} \quad (8a)$$

and

$$\frac{L}{L_0} = \frac{\eta_B I_e}{\eta_{B0} I_{e0}} = \left(\frac{\tau_e}{\tau_{e0}} \right)^{1/2} = \left(\frac{\eta_B}{\eta_{B0}} \right)^{1/2} \quad (8b)$$

These L/L_0 data are thus independent of excess current effects (space charge recombination, surface leakage and possible tunnelling), as well as hole diffusion into the n-side of the function, and allow a direct measure of the change in bulk efficiency. These data were plotted in figure 7 for samples RP 55-35, RP 78-29 and RP 71-39. (This last sample was placed in an oven at higher temperature (250°C) and unbiased.) Note that for both biased samples $L/L_0 = 0.75$ after the first hour of aging. The corresponding bulk efficiency ratio is $\eta_B/\eta_{B0} = (L/L_0)^2 = 0.56$. This indicates that the so-called "rapid" component of aging in these LEDs is a bulk recombination effect unrelated to surface contamination which may accrue gradually in the course of aging.

The remaining factor in equation 4 is the ratio of diffusion to total diode current. This efficiency, like the injection ratio, R , can actually be enhanced during bulk degradation. Qualitatively, this enhancement may be understood as follows: As a consequence of bulk degradation,

the diffusion lengths of minority carriers are reduced, thus increasing total diffusion current at a given level of bias voltage. For diodes such as we are considering here, where rapid bulk degradation can occur, this effect can initially outstrip the increase in nondiffusion current components.

Even an approximate calculation of the injection efficiency is complicated in two respects: Accounting for the voltage dependence of non-diffusion current components as the diodes degrade and measuring the initial diffusion current. In order to obtain a reasonable estimate of injection efficiency variation, we make the following assumptions: The voltage dependence of all nondiffusion current components, throughout degradation, will be accounted for by an approximate space-charge current model:

$$I_{sc}(V) = I_{sc}^0 e^{qV/2kT} \quad (9)$$

The assumption that this equation is valid throughout degradation, despite the evidence of figure 5, will make the calculation of η_{inj} pessimistic as degradation proceeds.

The initial diffusion current I_{do} is then taken to be the difference.

$$I_{do}(V) = I_o(V) - I_{sco}(V) \quad (10)$$

where $I_o(V)$ is the total initial measured current at V . Subscript o indicates the undegraded case. An estimate of the increase in total diffusion current requires the result obtained above that injection ratio R ,

does not change significantly with degradation, i.e., the increase in hole injection is proportional to the increase in electron injection. From equations 7 and 8 it can be shown that:

$$\frac{I_d}{I_{do}} = \left(\frac{\tau_{eo}}{\tau_e} \right)^{\frac{1}{2}} = \frac{L_o}{L} \quad (11)$$

Injection efficiency may then be estimated from L-I-V data taken at various stages of degradation. Equation 9 is used to (pessimistically) extrapolate nondiffusion currents while equation 11 is used to estimate the increase in diffusion current with degradation. The result of such calculations, based on the data of figures 7 and 8, is shown in figure 15. Here we have plotted the estimate of η_{inj} vs. time at two different test currents for two different samples. Notice that the total variation of η_{inj} is less than 7% of its mean value at 10 mA for RP 55-35 and even less for RP 78-29. Even for the worst case (1 mA meas. for RP-55-35) the relative value has dropped ~20% at 1,000 hours, while the total degradation of quantum efficiency $\eta/\eta_0 \approx 0.1$. Therefore the degradation of injection efficiency is not a major factor in the degradation of these GaP LEDs, and may in fact be partly offset by an increase in injection ratio. Therefore, in addition to the experimental evidence establishing the large reduction of bulk radiative efficiency there is further data which strongly suggests that the influence of the other factors in equation 4 have minimal net effect on the degradation of external electroluminescent efficiency.

VII. SUMMARY AND CONCLUSIONS

This paper has shown detailed data on the elevated temperature degradation characteristics of red-light-emitting GaP LEDs. Analysis of the data has established these points: 1) Degradation of this material is dominated by reduction of the radiative recombination efficiency of minority carriers, 2) Other degradation modes have negligible influence over the useful operating life of the device. 3) The current dependence of degradation has been measured at ambient temperatures of 150°C and 200°C. At a standard measurement current of 10 mA, MTF is approximately inversely dependent on stress current ($MTF \propto I_{\text{stress}}^{-1.13}$). When the stress and measurement currents are the same, the current dependence of degradation is weaker ($MTF \propto I^{-.56}$). Valuable discussions with J. S. Jayson, S. Knight, W. H. Eckton, Jr., P.D. Dapkus, R. Moest and V. G. Keramidas are gratefully acknowledged. Particular thanks are due to R. H. Saul for a critical review of the manuscript.

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FIGURE CAPTIONS

- Fig. 1 Relative degraded efficiency (η/η_0) as a function of time, for four groups of diodes stressed at 30 mA at a junction temperature of 220°C. Efficiency measurements were made at 10 mA.
- Fig. 2 Degradation of RP 55-35 at the temperature and stress conditions indicated. The abscissa is linear in $(\text{time})^{1/2}$. The linear time scale is shown at the top of the figure.
- Fig. 3 The effect of varying the current at which η/η_0 is measured, on a single group of diodes aged under the stated conditions.
- Fig. 4 Degradation of groups of diodes placed in a 150° ambient and stressed at 6, 10 and 30 mA. The consequent junction temperatures are shown. All efficiency measurements (η/η_0) are at 10 mA.
- Fig. 5 The L-I-V characteristics of a typical LED before and after severe degradation. Light output at fixed voltage is sharply reduced. Forward current at 1.4V is increased, but becomes less voltage dependent ($n > 2$).
- Fig. 6 The dependence of absolute quantum efficiency (η) on current, before and after severe degradation. The peak in efficiency of the undegraded sample (at 3.5 mA) has all but flattened completely.
- Fig. 7 Relative light measured at constant voltage (L/L_0) for three groups of LEDs. RP 55-35 and RP 78-29 were stressed at 30 mA in a 200°C ambient ($T_j = 220^\circ\text{C}$), RP 71-39 was stored, unbiased, in a 250°C ambient.
- Fig. 8 The growth of total device current at 1.4V. Samples and stress conditions are as indicated in the figure. At such low bias levels, the device current is totally dominated by excess current components.
- Fig. 9 Arrhenius plot of elevated temperature stress data on slice RP 55-35. η/η_0 measurements at 10 mA and 30 mA are indicated. The effect of using both MTF and τ as characteristic degradation times is shown.

- Fig. 10 Arrhenius plot of elevated temperature stress data of 3 separate groups of LEDs obtained from different slices. These diodes were stressed at 30 mA. η/η_0 was determined at 10 mA.
- Fig. 11 Same as Fig. 10 except that η/η_0 was determined at 30 mA.
- Fig. 12 Arrhenius plot of elevated temperature stress data on slide RP 55-35, for three different values of stress current. Note the relative insensitivity of the activation energy to stress current. τ is used as time parameter because failure has not been obtained on least-stressed samples.
- Fig. 13 The dependence of characteristic failure time (τ or MTTF) on stress current. Here the data of Fig. 4 has been analyzed and corrected to a junction temperature of 150°C. The dependence of characteristic failure time on stress current is approximately inverse whether τ or MTTF is used.
- Fig. 14 The dependence of MTTF on device stress current. This figure shows data taken at ambient temperatures of 150°C (T_j corrected to 150°C) and 200°C (T_j corrected to 200°C). Note that at both temperatures, when degradation is measured at the stress current, the current dependence of MTTF is the same.
- Fig. 15 Estimated time evolution of LED injection efficiency (based on the data of Figs. 7 and 8) at two levels of measurement current.

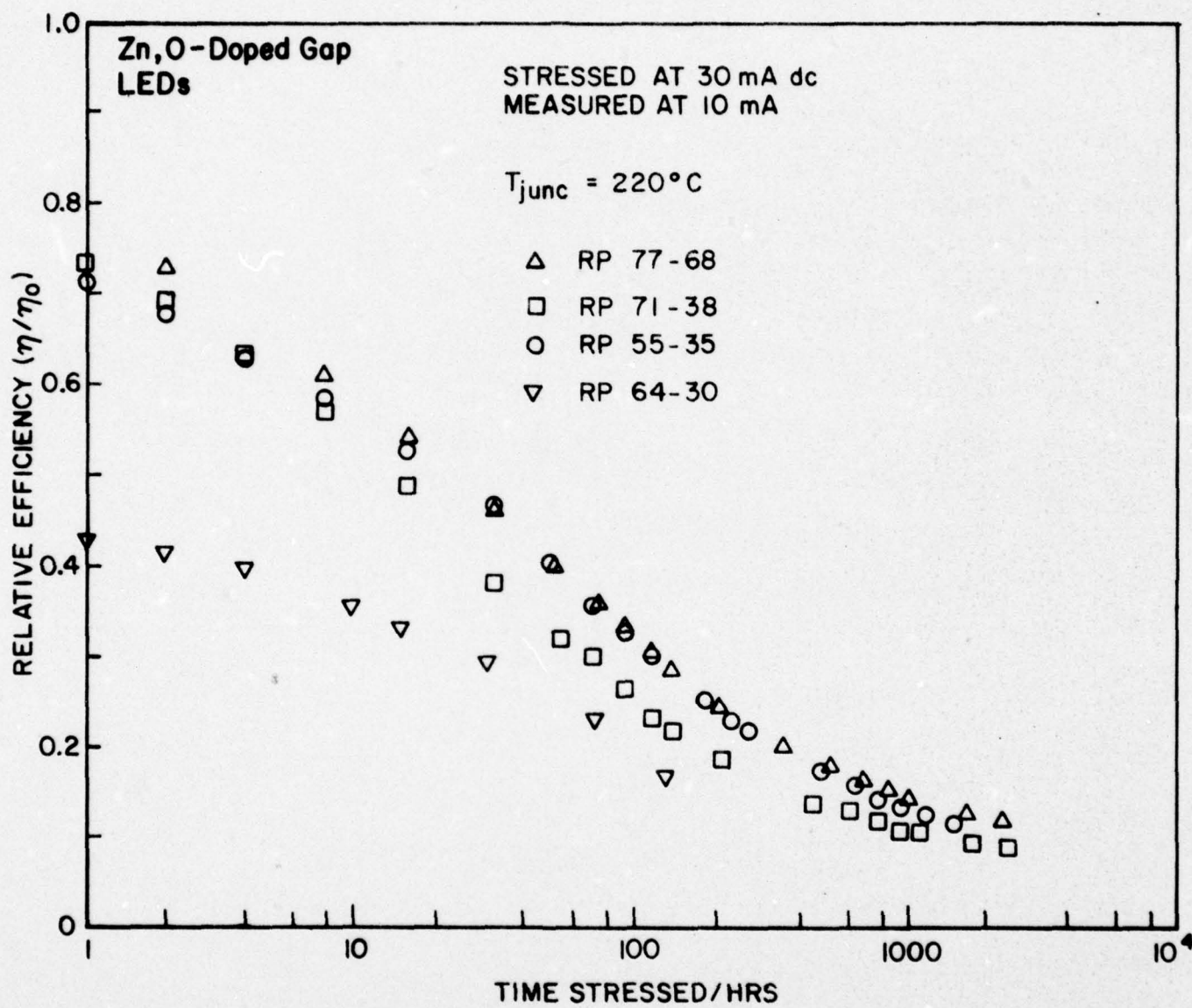


Fig. 1

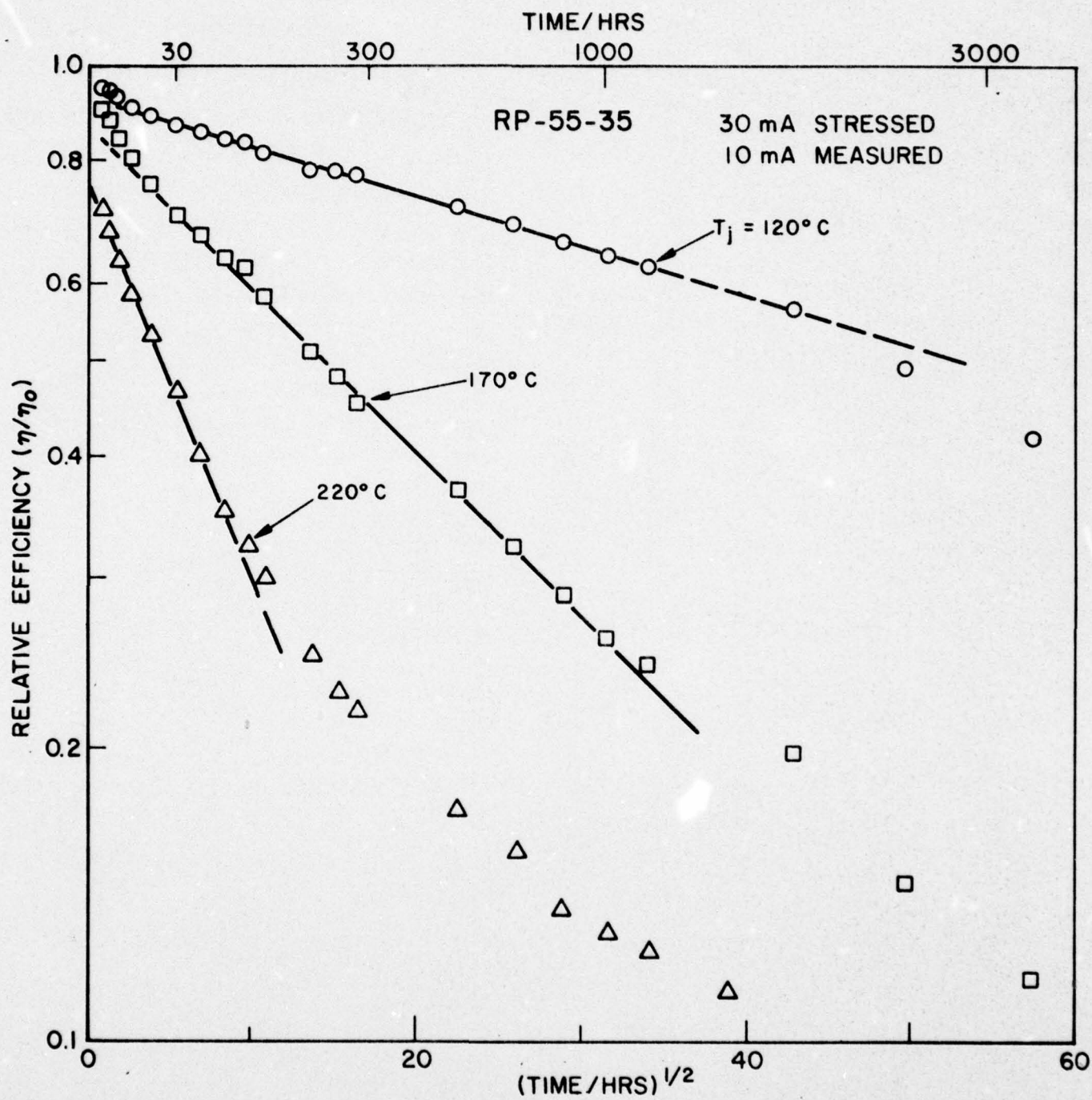


Fig. 2

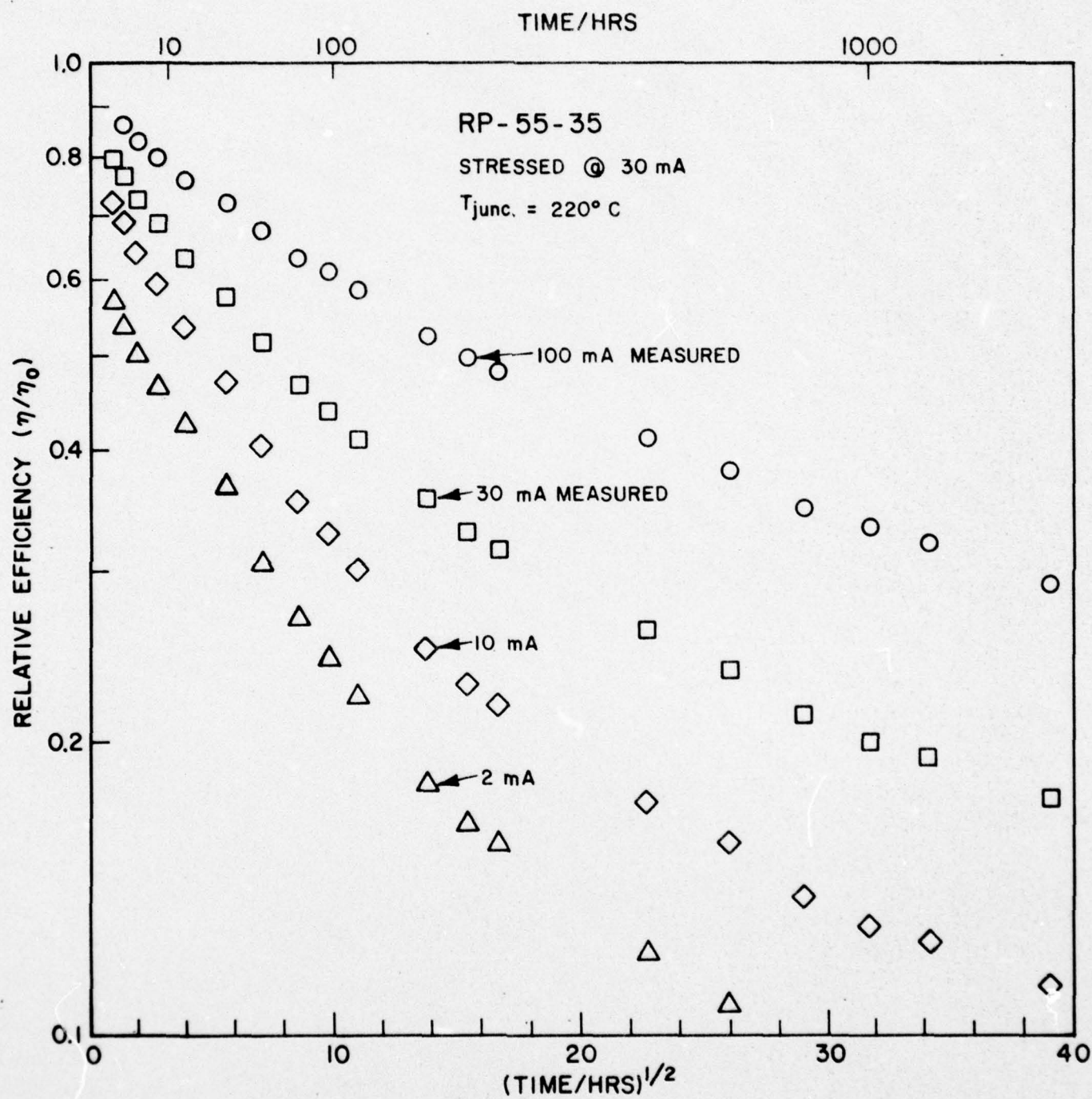


Fig. 3

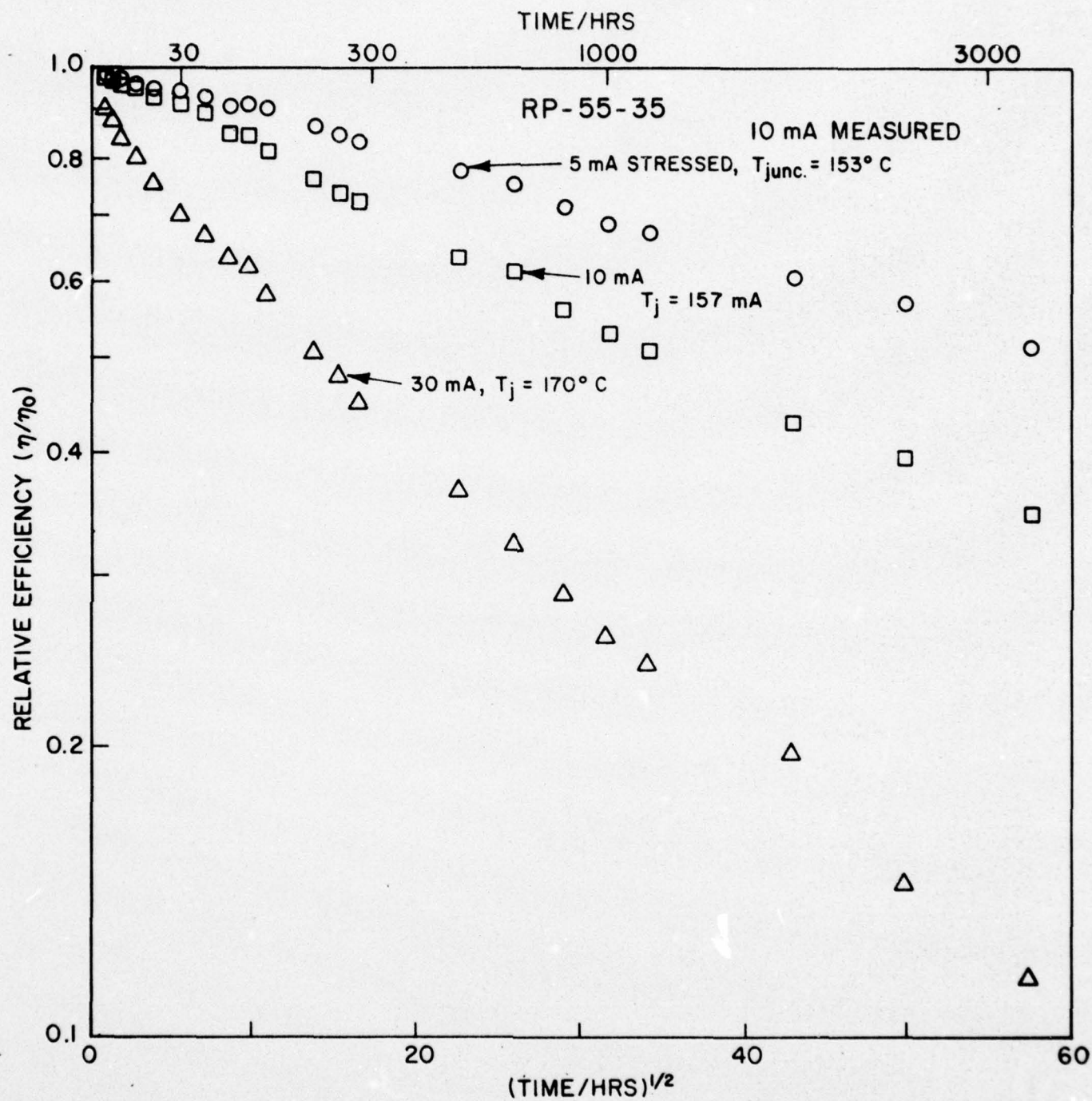


Fig. 4

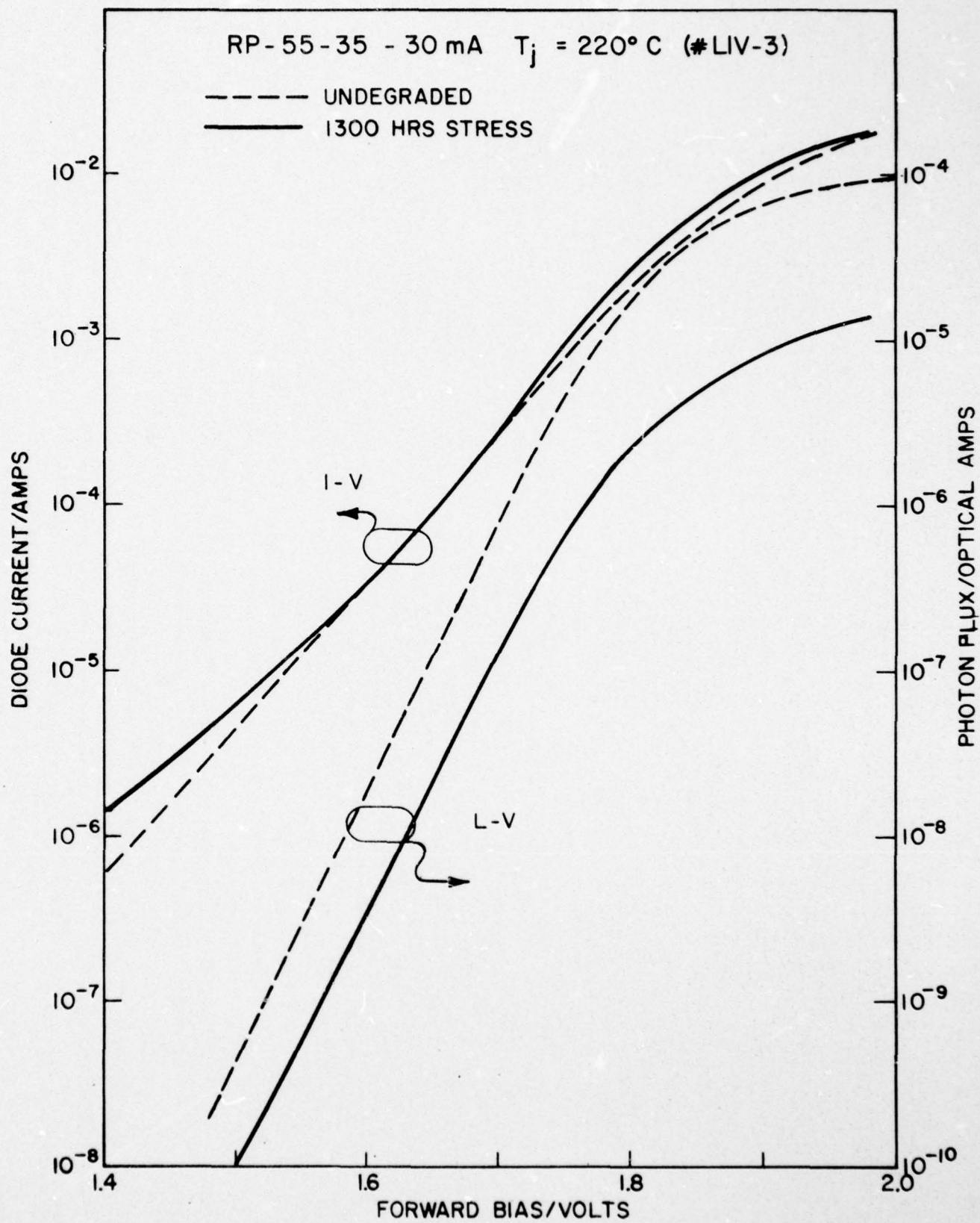


Fig. 5

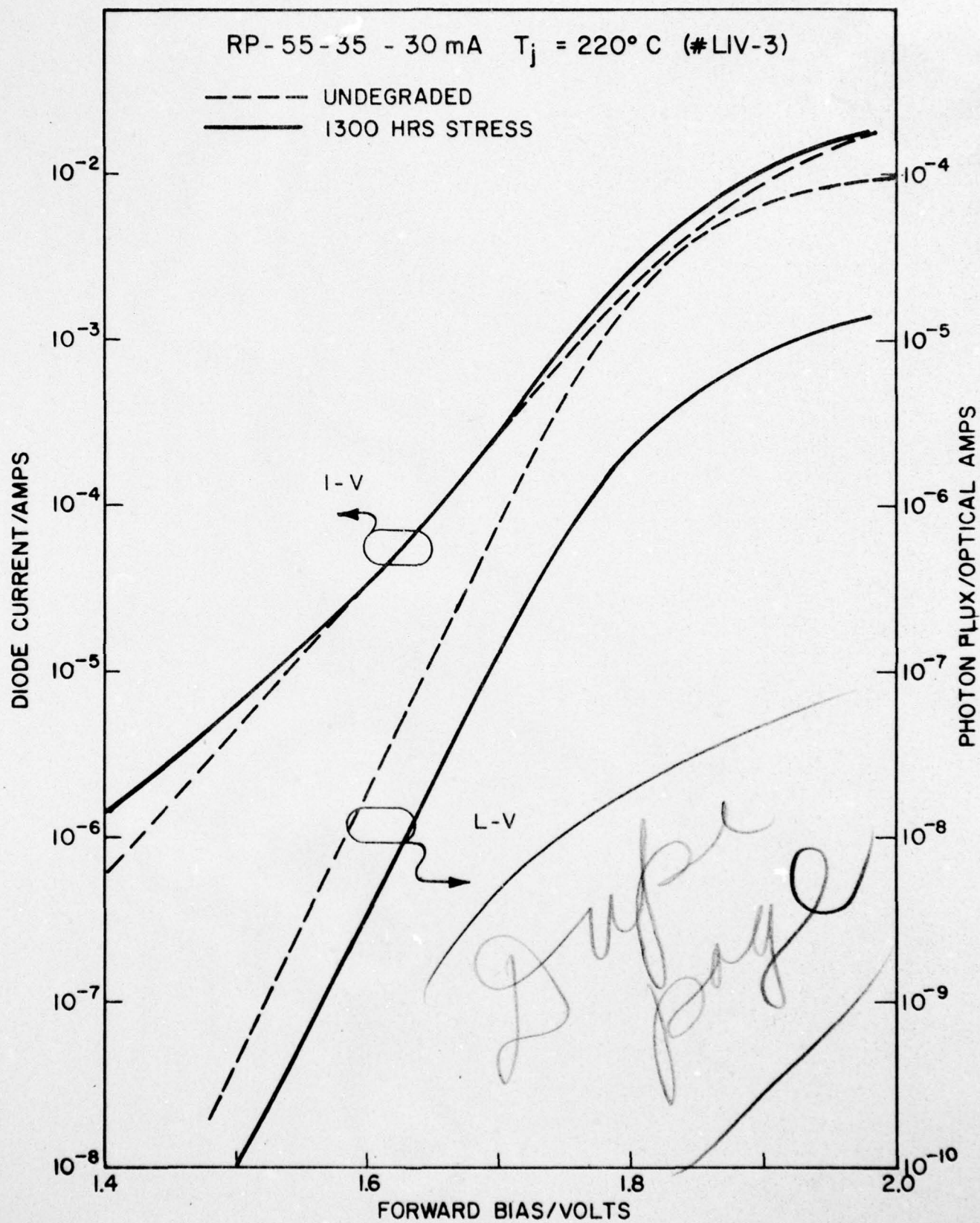


Fig. 5

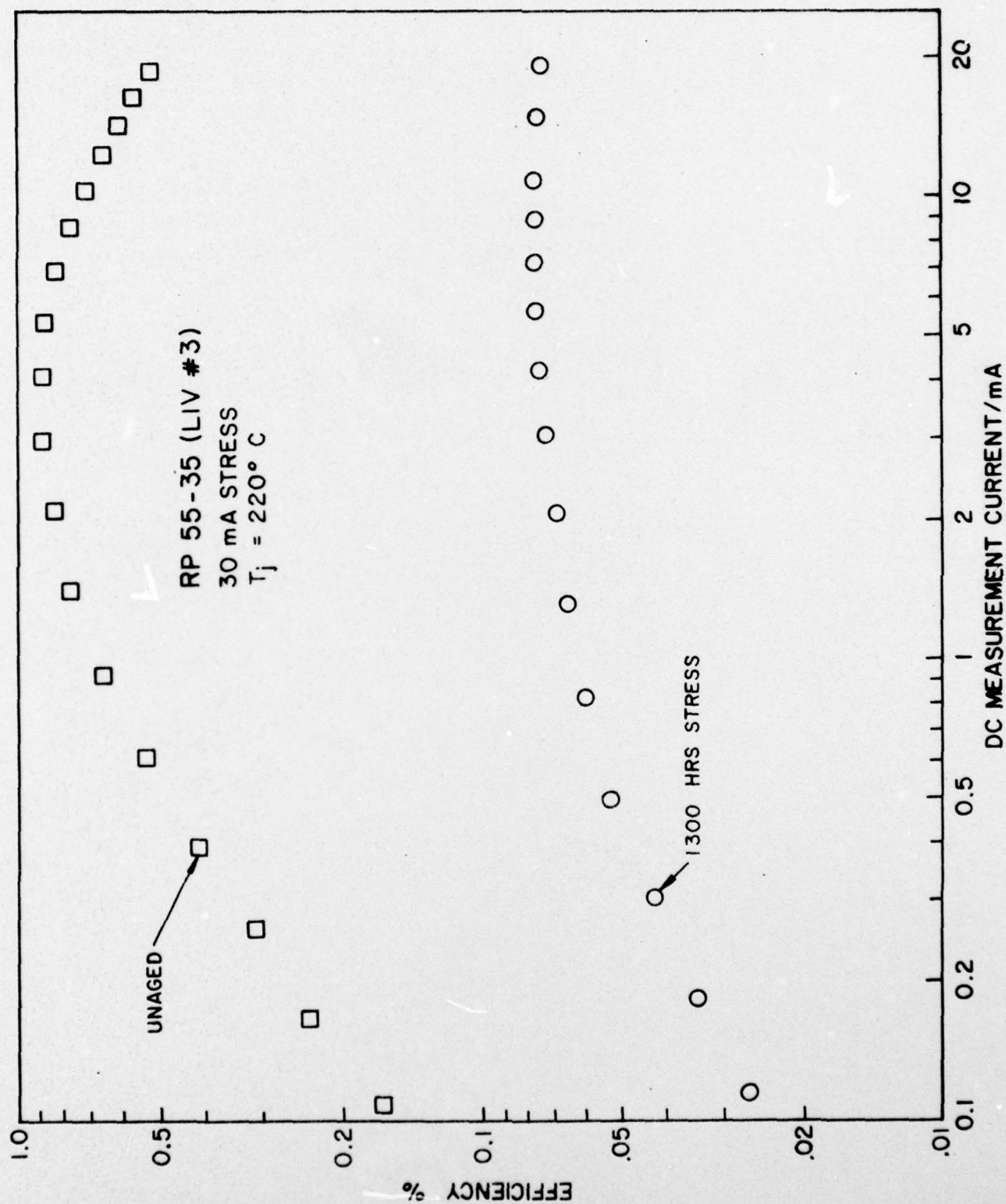


Fig. 6

DEGRADATION OF LIGHT OUTPUT AT FIXED VOLTAGE BIAS
L MEASURED AT 1.7V

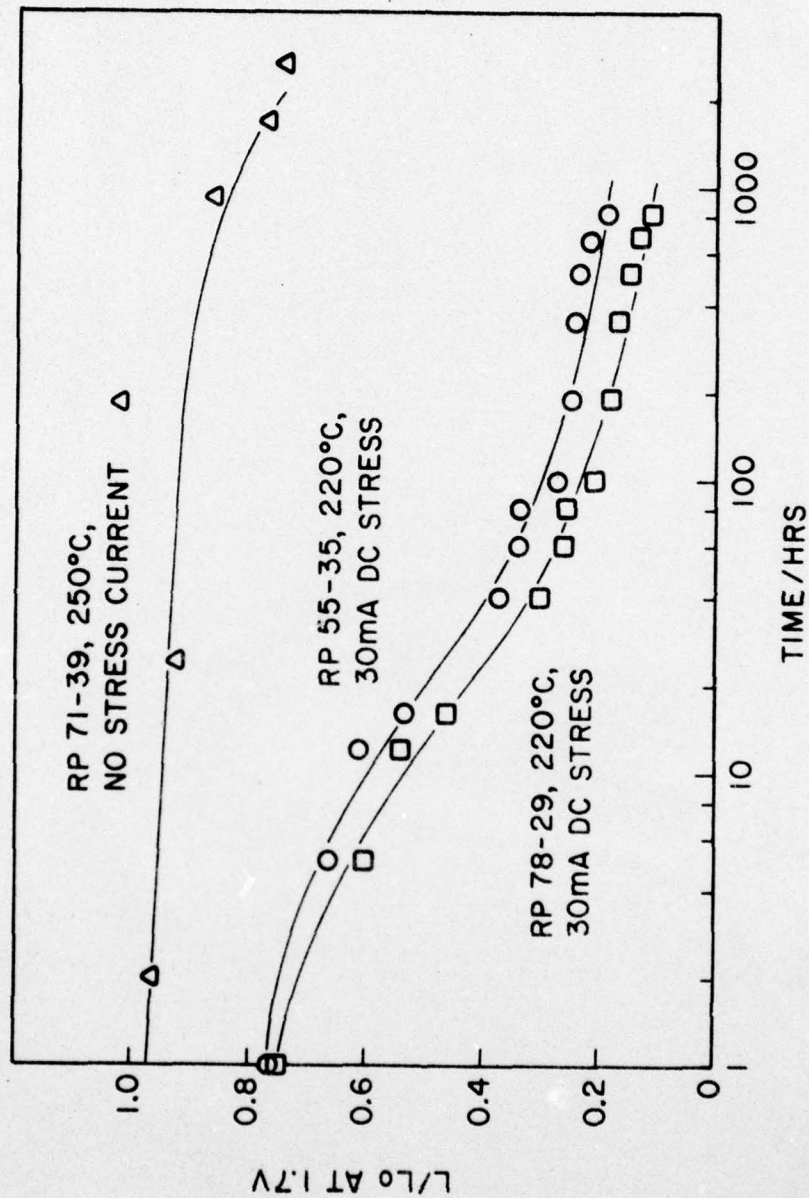


Fig. 7

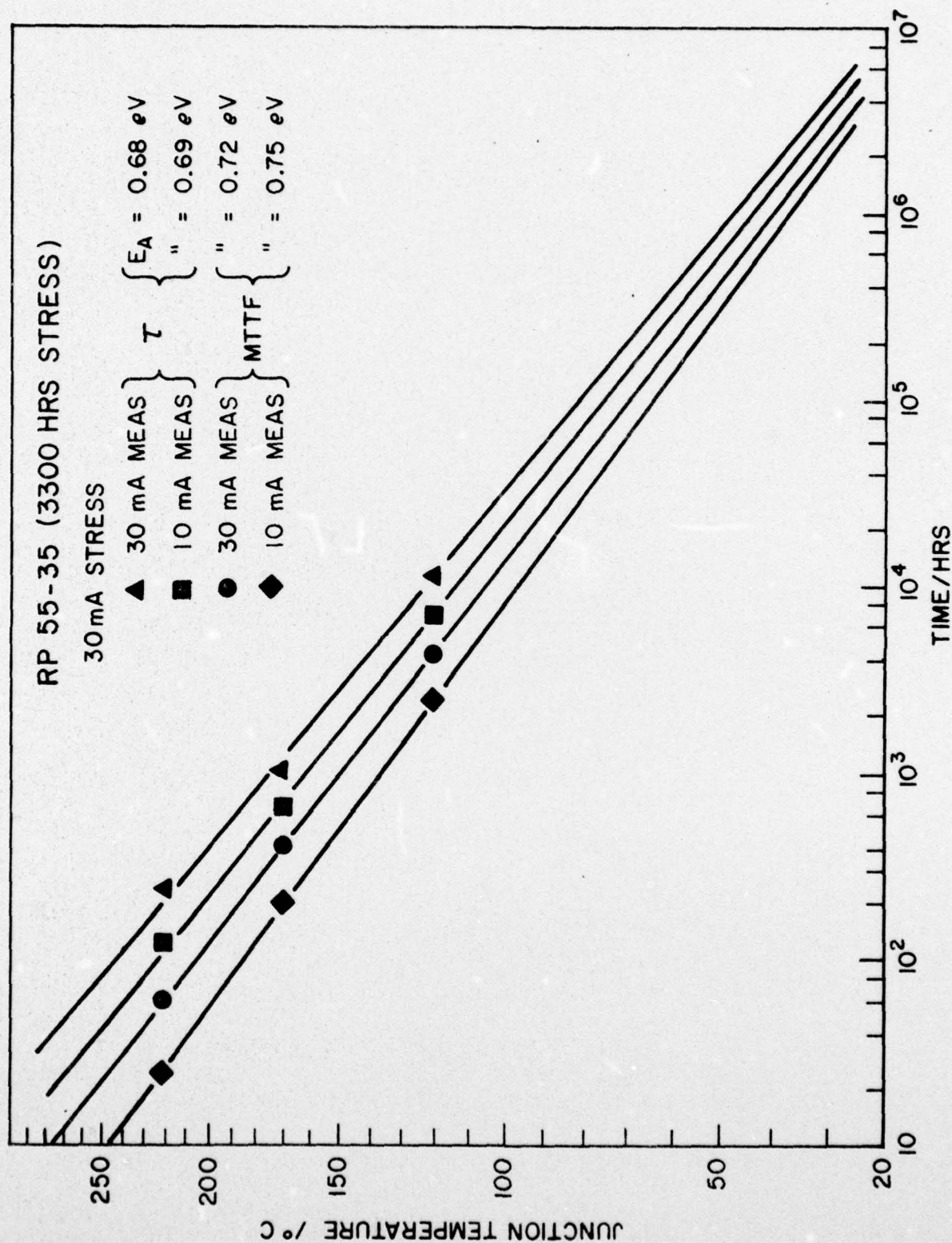


Fig. 9

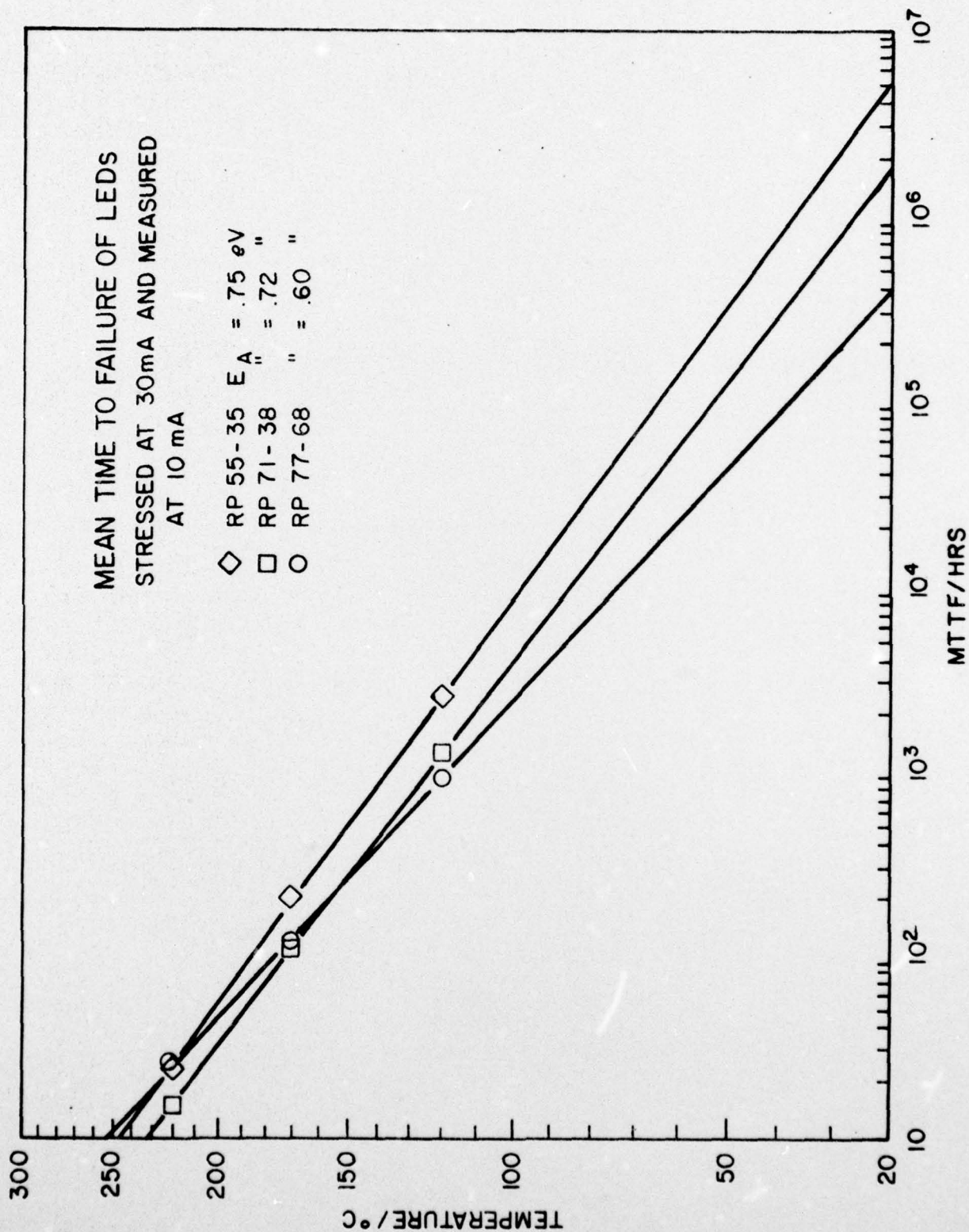
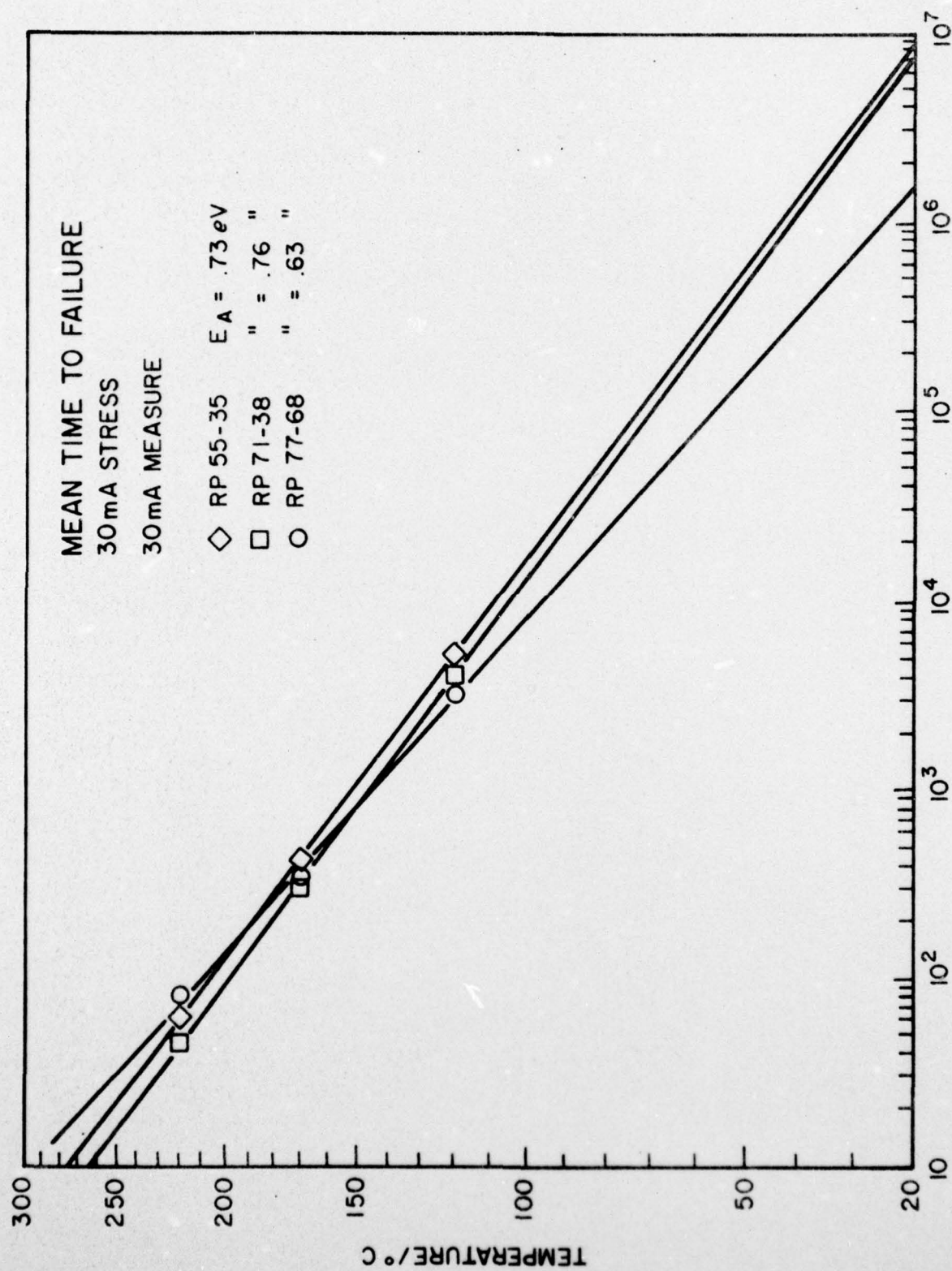


Fig. 10



MTTF/HRS
Fig. 11

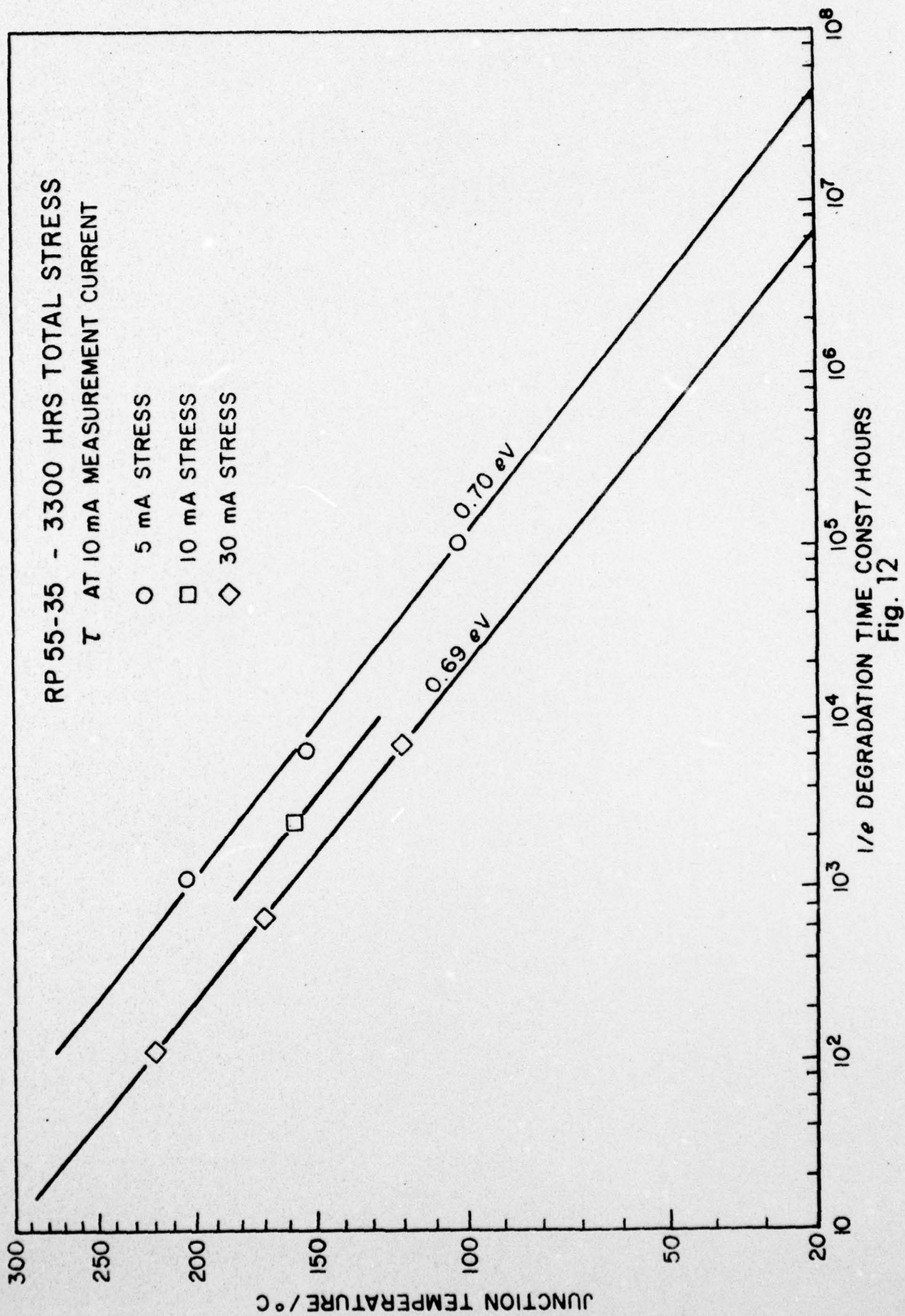


Fig. 12

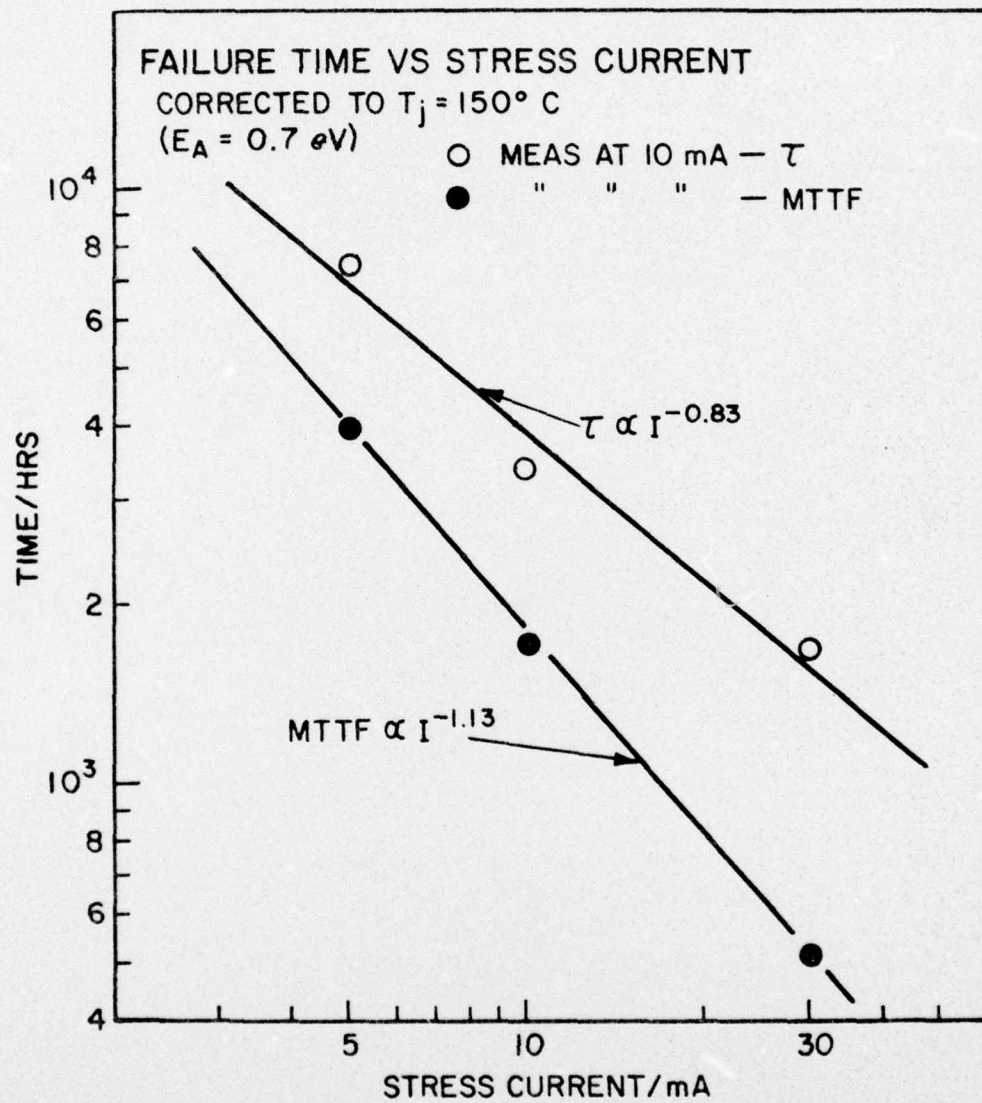


Fig. 13

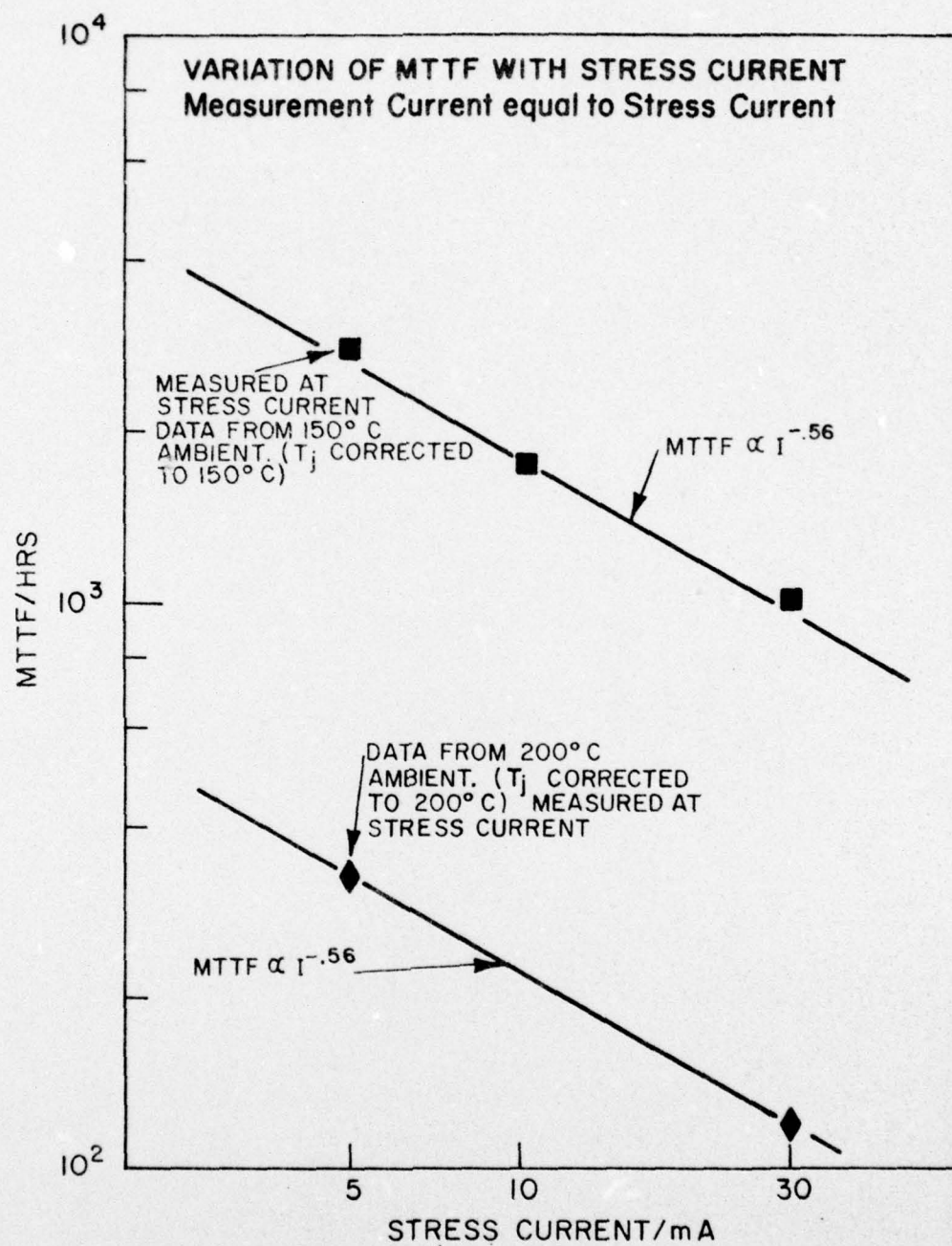


Fig.14

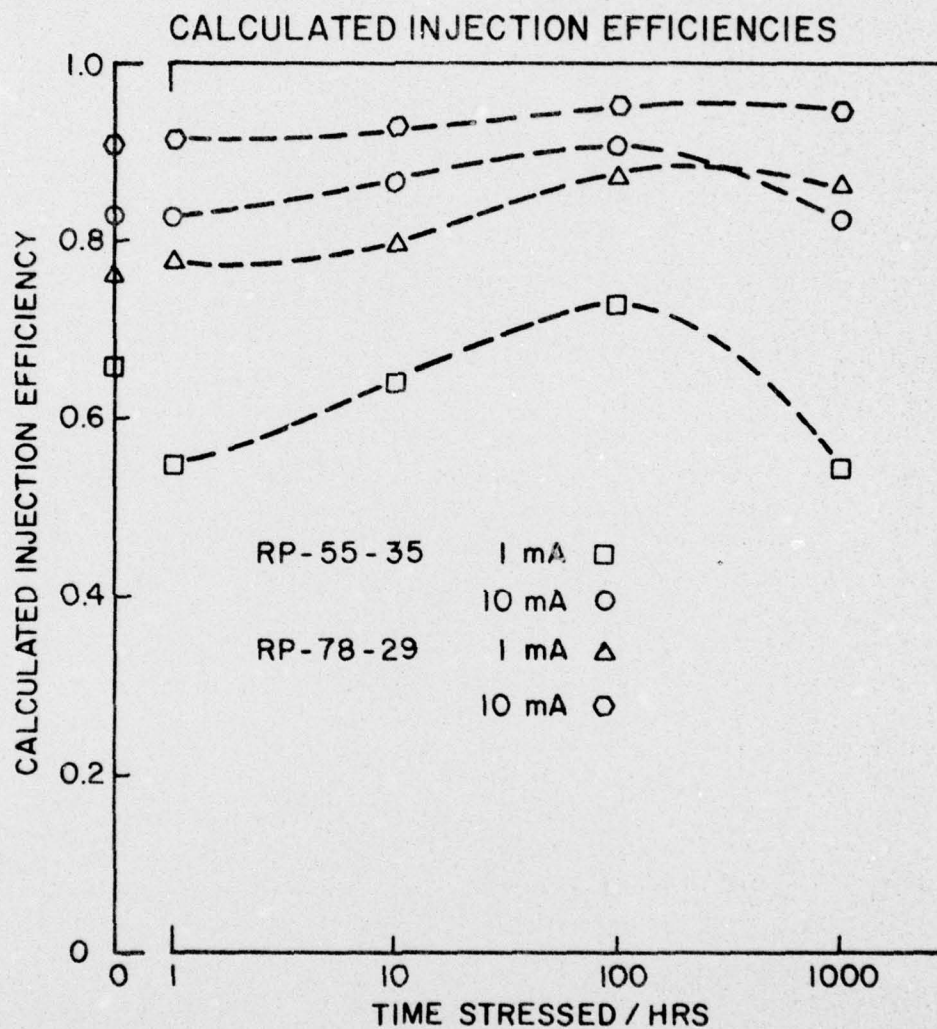


Fig. 15

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- PP 226
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