Reliability

Summary of SEC555 AlGaAs:Si IRED Chip Long-Term Operating Life Study

IRED CHIP DEGRADATION STUDIES

Honeywell has an ongoing study of degradation of radiant output over time as a function of temperature and current for the SEC555 aluminum gallium arsenide (AlGaAs) infrared emitting diode (IRED) chip. This IRED chip is used in a variety of Honeywell's commercial components and assemblies. The results of this study through October 1987 are presented below.

INTRODUCTION

Honeywell is committed to the manufacture of reliable, high quality optoelectronic products. An ISO9001 based quality system is maintained, providing the necessary controls to assure that all products meet or exceed the specified requirements. To assure continuing performance under conditions of environmental and mechanical stress, periodic reliability testing is performed on samples from production. All new products are thoroughly tested and characterized before introduction, with particular attention given to those parameters which relate to operational life and reliability.

Optoelectronic components, being semiconductors, share with all other semiconductor devices a susceptibility to certain mechanical failure modes. To be acceptable, semiconductors must withstand stress of temperature, humidity, mechanical shock and vibration. The industry employs established test methods and reliability projection techniques to ensure acceptability.

Degradation of radiant output is a reliability factor that is unique in infrared emitting diodes (IREDs). Honeywell has pioneered the development of a characterization model which projects the effect of this phenomenon on component reliability. Validation of this model continues as Honeywell products, and those of other manufacturers, are tested. In addition, the resulting knowledge of factors affecting reliability aids in the improvement of products and processes.

The SEC555 chip is an aluminum gallium arsenide silicon-doped (AlGaAs:Si) infrared-emitting diode (IRED) chip. The SEC555 chip is widely used in Honeywell component packages and higher-level assemblies. This report details the results of an ongoing study to characterize the fundamental long-term degradation mechanisms in the SEC555. The results are contrasted to the behaviour of the older GaAs:Si SEC450 IRED chip.

MECHANICAL RELIABILITY

Mechanical integrity of optoelectronic components, and the range of stress conditions over which reliable operation results, are of critical importance to the system designer. Optoelectronic components exhibit failure rates and mechanical wear-out characteristics which fit the well known "bath tub curve" (Figure 1) common to semiconductor devices. IRED power output degradation is a wear-out mechanism.

Components utilizing the SEC555 IRED chip are available in two basic package types: hermetic glass-lens-to-metal-header devices and plastic molded-lead-frame devices. Figure 2 summarizes these packages and their properties.

Figure 1 Semiconductor Failure Rate as a Function of Time

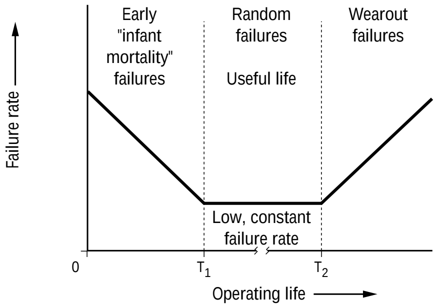


Figure 2 Honeywell Optoelectronics Products Utilizing AlGaAs:Si LED Chip

Product	Package Type	Thermal Resistance (No Heat Sink)	Maximum Operating Temperature
SE3470 SE5470	Hermetic TO-46	370°C/W	125°C
SEP8790	Plastic TO-46	750°C/W	125°C
SEP8703	Plastic $T1^3/_4$	750°C/W	100°C

Reliability

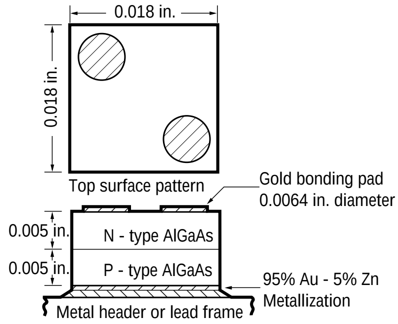
Summary of SEC555 AlGaAs:Si IRED Chip Long-Term Operating Life Study

SEC555 CHIP STRUCTURE

The SEC555 IRED chip is an aluminum gallium arsenide, silicon-doped (AlGaAs:Si) structure. The structure is based on the original 1977 paper by Ralph Dawson, "High-Efficiency Graded Band-Gap AlGaAs Light Emitting Diodes," Journal of Applied Physics 48, 2485-92, 1977.

Figure 3 shows the chip construction. The AlGaAs PN junction is formed by liquid-phase-epitaxy (LPE) growth of AlGaAs layers onto GaAs substrates. Wafer processing produces the final chip pattern with N/P metal contacts. Radiant emission occurs over the full 18 x 18 mil area of the chip junction with side and top surface emission. The metal bond pads partially obstruct the top surface emission.

Figure 3 SEC555 LED Structure



The mechanical adhesion of the chip to the metal header employs a gold-tin eutectic die attach. Mechanical adhesion of the chip to metal lead frames employs a gold-filled conductive epoxy. Gold ball bonding contacts the top surface N-side of the junction.

POWER OUTPUT DEGRADATION THEORY

Optical power output degradation during operation has been established as a wear-out mechanism for the SEC555 IRED chip. Although all devices degrade in this manner with time, they do so with widely varying rates, resulting in a non-constant failure rate. This process varies also with temperature and operating current. Circuit and system designers must have knowledge of the magnitude of typical and worst case IRED degradation to assure adequate optical power output throughout the intended design life of the system. The Honeywell approach to this requirement is summarized in the following section.

QUANTUM EFFICIENCY

Optical power output of an IRED is directly proportional to the applied forward current:

Equation (1)

$$P_o = \eta E\, I_F$$

Where

P_o = Optical power output in watts
η = LED external quantum efficiency
E = Energy per photon emitted in eV
I_F = Applied forward current in amps

Optical power output degradation of an IRED at a fixed operating current (I_F), which is the normal mode for industrial applications, will occur as a result of a decrease in the IRED external quantum efficiency (η).

I-V CHARACTERISTICS

The forward current-voltage characteristic of a semiconductor PN junction diode has two current components, diffusion current and space charge recombination current:

Equation (2)

$$I_F = A[\exp(qV_F/kT)] + B[\exp(qV_F/2kT)]$$

Where

q = Electronic charge (1.6×10^{-19} C)
I_F = Forward current
V_F = Forward voltage
k = Boltzmann's constant
T = Junction temperature (K)
A = Diffusion current coefficient
B = Space-charge recombination current coefficient

For an IRED, only the diffusion current component contributes to radiative (light emission) current. The space-charge recombination current contributes to non-radiative current. The ratio of radiative to non-radiative current at a fixed forward current, which is the normal mode for industrial applications, directly affects the IRED external quantum efficiency. Quantum efficiency directly relates to IRED emitted power as was previously shown by equation (1).

AlGaAs VERSUS GaAs

The AlGaAs:Si IRED chip developed by Dawson has become popular in the optoelectronics industry because it achieves a higher quantum efficiency than the industry standard GaAs:Si IRED chip developed in the 1960s.

Reliability

Summary of SEC555 AlGaAs:Si IRED Chip Long-Term Operating Life Study

The AlGaAs chip differs from the GaAs chip in three electro-optical characteristics:

1. The power output is 1.5 to 2 times higher
2. The peak wavelength is 880 nm instead of 940 nm
3. The forward voltage (V_F) is slightly higher

The higher quantum efficiency is attributed to photon recycling in the graded bandgap p-AlGaAs layer ("Photon Recycling in AlGaAs:Si Graded Band-Gap LEDs," J. Appl. Phys. 50, p. 6353-6362, 1979). The theory is that photons emitted downward in the AlGaAs layer are absorbed in narrower bandgap material and re-emitted at the longer wavelength, with most of the downward emitting photons getting out of the IRED chip. In uniform bandgap p-GaAs layers this photon recycling does not occur.

The peak wavelength shift and increased forward voltage of AlGaAs versus GaAs are both due to the wider bandgap at the junction with the aluminum addition to the crystalline lattice.

Previous studies have shown from experimental data that as the GaAs:Si (SEC450) IRED chip ages the radiative ("kT") current component decreases for a fixed forward current due to a decrease in the diffusion current coefficient A. The radiative current decrease causes decreased IRED optical power output. The mechanism for degradation appears to be a bulk diffusion which may be related to the silicon dopant since the diffusion component changes only for silicon doped GaAs structures. As will be shown later for data in this study, similar decreases in radiative output due to a decrease in the diffusion current coefficient A occur for the AlGaAs:Si IRED chip and possibly are related to the photon recycling phenomena. Visual inspection of degraded devices shows only a general "dimming" of the radiant output for both GaAs:Si and AlGaAs:Si structures with no dark-line-defects. Dark-line-defects are well known for zinc-diffused GaAs and double-heterostructure AlGaAs devices.

TIME DEPENDENCE

Time dependence of GaAs:Si IRED degradation has been measured by Honeywell and others. Logarithmic degradation rate versus square root of time for a wide range of degradation rates has been observed. The degradation rate can be described by a simple one-stage equation of:

Equation (3)

$$P_o(t) = P_o(t=0)[\exp(-(t/\tau)^{0.5})]$$

Where

$P_o(t)$ = Optical power output at time t

P_o (t=0) = Initial optical power output

t = Total operating time

τ = Degradation characteristic time constant

As will be shown later for experimental data, the SEC555 AlGaAs:Si IRED chip exhibits a multistage degradation process with a time dependence more complex than the above equation.

TEMPERATURE/CURRENT DEPENDENCE

The temperature and current dependence of the GaAs:Si IRED degradation process is well described by Arrhenius's Law:

Equation (4)

$$t = \tau_o[\exp(E_A/kT)]$$

Where τ_o is current dependent and assumed to have power-law relationship.

Equation (5)

$$t = A_1(I_F)^n[\exp(E_A/kT)]$$

Where

A_1 = Constant of proportionality

I_F = Applied forward current in amps

n = Exponent of current dependence

E_A = Thermal activation energy in eV

k = Boltzmann's constant

T = Operating junction temperature

The above equations which fit the GaAs:Si IRED do not work well for the multi-stage power output degradation mechanism of the AlGaAs:Si. A suitable model which describes the effects of temperature and/or operating current on the AlGaAs:Si IRED has not been developed yet.

STATISTICAL VARIATION OF IRED DEGRADATION

Analysis of IRED degradation is a statistical process which deals with varying degradation rates within a given sample of units. Using statistically significant samples, previous studies have shown a log-normal distribution of degradation rate for the GaAs:Si SEC450 IRED chip. In this study few actual failures (for 3 dB power output drop) have been observed, but projections on time of failure indicate a log-normal failure distribution also, despite a more complex degradation process. Generally, the end of IRED operating life is defined as the point in time when the power output

Reliability

Summary of SEC555 AlGaAs:Si IRED Chip Long-Term Operating Life Study

drops to one-half its initial value (50% or 3 dB drop). If end-of-life data for an IRED group tested to failure is plotted on log-normal scales of % population versus logarithm of operating lifetime, a straight line with a point of 50% of the population representing the median half-life of the group should result. The median half-life of an IRED product is a useful figure of merit for comparing products and projecting system lifetimes.

DESIGN AND ANALYSIS OF BURN-IN

In this study a SEC555 IRED chip lot was assembled in hermetic TO-46 packages and placed on heat-sinked burn-in at several temperatures and forward currentconditions. Initial and periodic measurements ofI-V-P data (forward current, forward voltage, and optical power output) were recorded using a Teradyne A360 test system.

Thermal resistance measurements along with power dissipation calculations determined the typical chip junction temperature for each burn-in condition.

Figure 4 summarizes the results to date of the ongoing burn-in study. A parallel study of the SEC456 GaAs:Si 18 x 18 IRED chip is compared to the SEC555 data in Figure 5. It is clear that the AlGaAs:Si chip behaves differently during aging. The GaAs:Si chip exhibits well-behaved temperature/current dependence for degradation rate. The AlGaAs:Si chip to-date does not exhibit a definite degradation rate temperature dependence. The AlGaAs:Si chip shows some current dependence for degradation but no parameters can yet be projected. For the conditions of T_c = 125°C, and I_F = 100 mA there are **no** failures in 1.5 million device-hours.

Figure 4 SEC555 Burn-In Test Summary (Chip Type: AlGaAs:Si, 0.018 in. x 0.018 in.)

Temperature	Forward Current	# Units	# Burn-In Hours	# Units Fail	Total Device Hours	Median Half-Life Hours
T_C = 80°C	100 mA	25	15,618	0	390,450	50,000
T_C = 100°C	100 mA	25	15,618	0	390,450	120,000
*T_C = 125°C	100 mA	25	15,690	0	392,250	250,000
T_C = 125°C	50 mA	25	15,628	0	390,700	160,000
*T_C = 125°C	100 mA	25	15,690	0	392,250	250,000
T_C = 125°C	150 mA	25	15,628	5	390,700	40,000
T_C = 125°C	200 mA	25	15,628	2	390,700	40,000

Figure 5 GaAs:Si vs AlGaAs:Si Burn-In Comparison
Chip Type: SEC456 GaAs:Si 18x18, SEC555 AlGaAs:Si 18x18
Package Type: Hermetic TO-46
Burn-In Sample: 25 Units per Burn-In Condition Burn-In Time: 15,600 Hours, 390,000 Device-Hours
Failure = 3 dB (50%) Power Output Drop

Case Temperature	Forward Current	GaAs:Si		AlGaAs:Si	
		# Fail	Median Half-Life	# Fail	Median Half-Life
80°C	100 mA	0	150,000 hours	0	50,000 hours
100°C	100 mA	2	80,000 hours	0	120,000 hours
*125°C	100 mA	10	26,000 hours	0	250,000 hours
125°C	50 mA	2	95,000 hours	0	160,000 hours
*125°C	100 mA	10	26,000 hours	0	250,000 hours
125°C	150 mA	6	21,000 hours	0	40,000 hours
125°C	200 mA	9	18,000 hours	0	40,000 hours

* Same group

Reliability

Summary of SEC555 AlGaAs:Si IRED Chip Long-Term Operating Life Study

Figures 6-9 show the SEC555 I_F-V_F changes for small and large optical power output changes during burn-in. The radiative current component change with significant IRED degradation is clearly shown in Figure 6. Figure 8 shows that the 2kT non-radiative current component does not change even for significant IRED degradation. These I_F-V_F characteristics for AlGaAs:Si are in agreement with the earlier studies of GaAs:Si.

The behaviour of power output versus time for various burn-in conditions are plotted in Figures 10-13. Figures 11 and 12 clearly show a two-stage degradation process in which a first stage of 1-2 dB rapid degradation is followed by a second stage of a very slow degradation. Figures 10 and 13 at lower temperatures or lower currents exhibit only one stage of constant degradation rate. It is not clear whether the lower stress conditions simply delay the onset of the second stage of slow degradation, or remove the conditions required for the second stage to occur.

The power output versus time graphs indicate the first stage degradation may in fact have a temperature/current dependence of degradation rate much like the previous GaAs:Si studies. Figures 15 and 16 show power output versus time plots of the SEC555 chip for much lower temperature/current stress conditions (25°C, 50 mA and 100°C, 20 mA) where virtually no degradation of power output occurs during the initial 1500 hours of operation, which supports this conjecture for the first stage degradation rate.

Figure 16 shows the log-normal statistical variation of the IRED degradation even with the two stage degradation rate. The dashed line shows the actual burn-in hours. The solid circle represents units with measured half-life. The open circles represent extrapolated half-life using the expected logarithmic power output versus square root of time behaviour. Figures 10 and 13 demonstrate that the first stage degradation process fits this behaviour.

An evaluation of competitive AlGaAs:Si products was conducted to determine if this two stage degradation was unique to the Honeywell product or was typical for the industry product. Figure 17 summarizes the results of a burn-in comparison between Honeywell and two competitive AlGaAs:Si suppliers, with Honeywell exhibiting the slowest degradation process. The power output versus time plots in figures 18-20 indicate the two stage degradation process is characteristic of the AlGaAs:Si product across the industry, with one manufacturer's process having significantly high failures during the firststage degradation process.

CONCLUSIONS

A burn-in study of the SEC555 AlGaAs:Si IRED chip has demonstrated the product is fundamentally reliable with fewer failures than the GaAs:Si IRED chip when failure is defined as a 50% drop in power output. For operating conditions of $T_c \leq 125°C$, $I_F \leq 100$ mA, the SEC555 IRED chip had zero failures in 1.5 million device hours based on a sample size of 150 units tested over 15,600 hours (see Figures 4 and 5).

Significant differences in degradation characteristics from previous GaAs:Si IRED studies were observed. A two-stage degradation process with rapid initial degradation followed by a second stage of very slow degradation is exhibited. Applications which require <10 % power output change in the IRED chip should be restricted to moderate temperatures and currents to avoid failures. No projections for the SEC555 product reliability over temperatures and/or currents other than the burn-in study conditions can be made yet.

A burn-in comparison of competitive AlGaAs:Si IRED products indicate the two stage degradation process is not unique to the Honeywell product, and that the Honeywell SEC555 IRED chip is one of the most reliable AlGaAs:Si products in the industry.

Reliability

Summary of SEC555 AlGaAs:Si IRED Chip Long-Term Operating Life Study

Figure 6 Typical P_o-V_F Change During Power Output Degradation for AlGaAs:Si IRED Chip

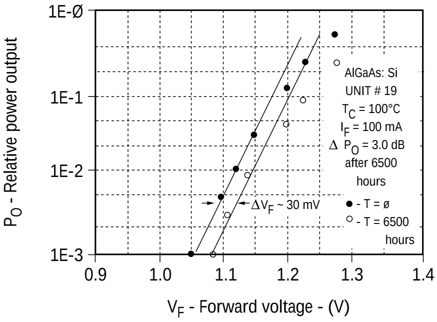


Figure 7 Typical P_o-V_F Change During Power Output Degradation for AlGaAs:Si IRED Chip

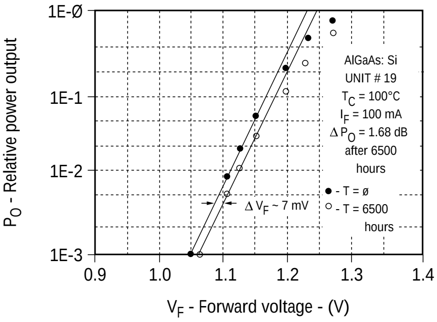


Figure 8 Typical I_F-V_F Change During Power Output Degradation for AlGaAs:Si IRED Chip

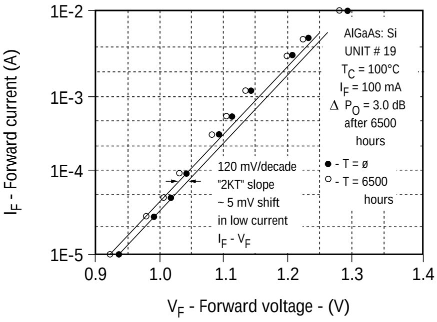


Figure 9 Typical I_F-V_F Change During Power Output Degradation for AlGaAs:Si IRED Chip

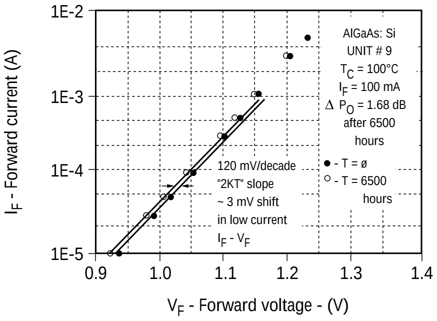


Figure 10 SEC555 Power Output vs Time Plots (T_{CASE} = 80°C, I_F = 100 mA, Burn-In Time = 15,618 hours)

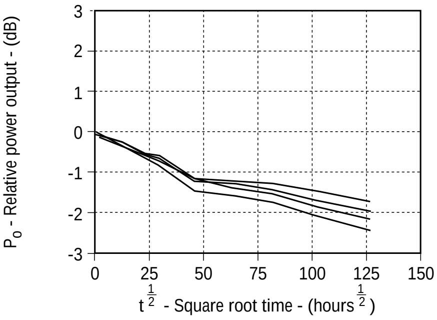
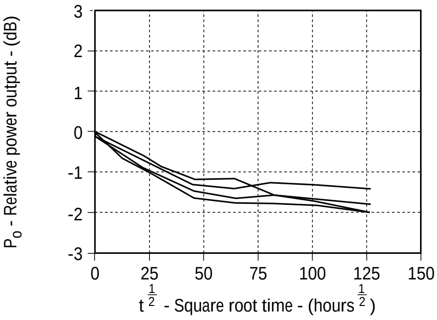


Figure 11 SEC555 Power Output vs Time Plots (T_{CASE} = 100°C, I_F = 100 mA, Burn-In Time = 15,618 hours)



Reliability

Summary of SEC555 AlGaAs:Si IRED Chip Long-Term Operating Life Study

Figure 12 SEC555 Power Output vs Time Plots (T_{CASE} = 125°C, I_F = 100 mA, Burn-In Time = 15,691 hours)

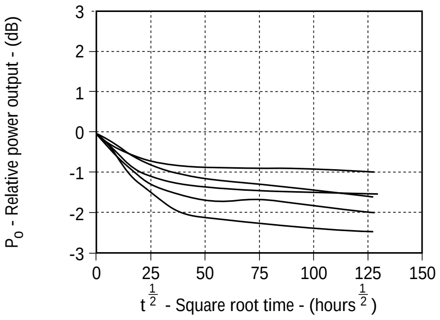


Figure 13 SEC555 Power Output vs Time Plots (T_{CASE} = 125°C, I_F = 50 mA, Burn-In Time = 15,629 hours)

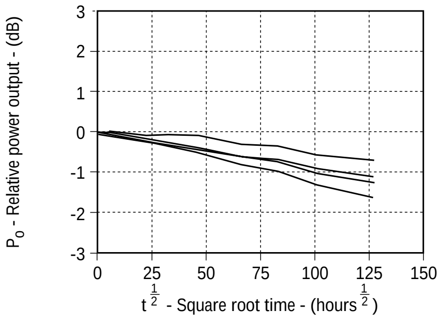


Figure 14 SEP8703 Plastic T1 3/4 Package, SEC555 AlGaAs LED Chip (T_A = 25°C, I_F = 50 mA, Burn-In Time = 1510 hours)

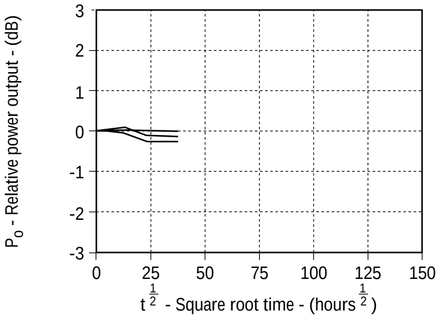


Figure 15 SEP8703 Plastic T1 3/4 Package, SEC555 AlGaAs LED Chip (T_A = 100°C, I_F = 20 mA, Burn-In Time = 962 hours)

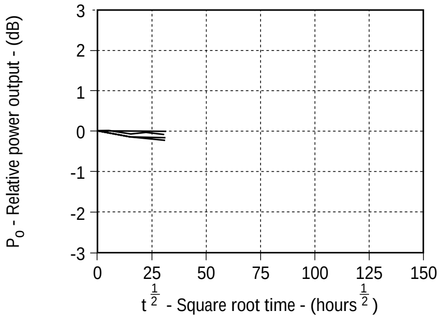


Figure 16 SEC555 Plastic T1 3/4 Package, Typical Log-Normal Distribution (T_{CASE} = 125°C, I_F = 150 mA DC, Burn-In Time = 15,628 hours)

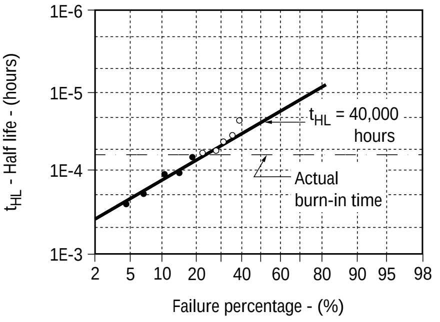


Figure 17 Competitive Burn-In Summary
Chip Type: AlGaAs:Si
Package Type: Hermetic TO-46 (T_{CASE} = 100°C, I_F = 100 mA, Burn-In Time = 5600 hours)

Manu-facturer	Number of units	Total device-hours	Number of units fail	Median halflife hours
Honeywell	10	56,000	0	50,000
G.	10	56,000	0	20,000
T.	10	56,000	5	6500

Reliability

Summary of SEC555 AlGaAs:Si IRED Chip Long-Term Operating Life Study

Figure 18 Competitive Burn-In, Manufacturer G, Power Output vs Time Plots (T_A = 100°C, I_F = 100 mA, Burn-In Time = 5600 hours)

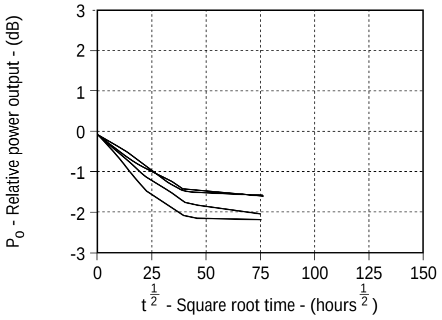


Figure 19 Competitive Burn-In, Manufacturer T, Power Output vs Time Plots (T_A = 100°C, I_F = 100 mA, Burn-In Time = 5600 hours)

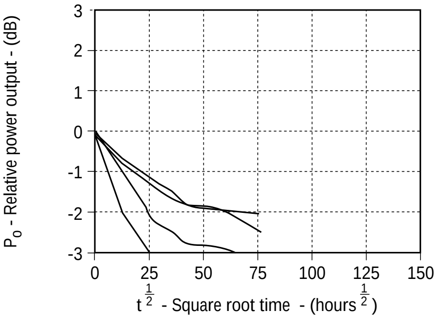


Figure 20 Competitive Burn-In, Honeywell SE3470, Power Output vs Time Plots (T_A = 100°C, I_F = 100 mA, Burn-In Time = 5600 hours)