Lifetime of BASS Devices in 50-Ohm Video Pulser Circuits

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ABSTRACT

The reliability of the optically triggered Bulk Avalanche Semiconductor Switch (BASS) has been assessed in a variety of test conditions. For a nominal characterization diagnostic, we have adopted a 50-ohm video transmission line having a pulsewidth of 0.5ns. At 11kV input voltage we have found BASS lifetimes in excess of 1 Billion pulses. This level of device lifetime is a record achievement for optically triggered semiconductor switches. The reliability distribution is found to be of Weibull type. We discuss the implications of the reliability distribution and the performance of the device during lifetime evaluations.

1. INTRODUCTION

Optically activated semiconductor switches may provide solutions for a new range of microwave generator applications[1]. The power levels which can be produced by individual devices have been shown to be very high -- demonstrated by the achievement of 100ps range risetimes at kV output voltages needed for high power applications[2]. Many groups have focussed upon the achievement of ever higher device powers, and ever larger physical implementations of optically triggered or photoconductive semiconductor switches (PCSS)[3,5]. Yet for practical applications in systems, the use of such devices depends not only on technological capability but also upon device reliability. Perhaps the largest barrier to the acceptance of these devices remains the unproven territory of device reliability [4].

The PCSS under evaluation by most groups can be broadly classified by their operational modes into Linear and Non-Linear (Avalanche) types. An independent estimate shows that the linear mode requires 500X the triggering light intensity of the Avalanche mode[5]. The linear-mode devices are operated with high doses of light, on the order of joules[6], so as to produce photoconductive response in a uniform flow of current. Devices of this type demonstrate normal resistance, and the temporal characteristic of the current pulse closely follows that of the light used for triggering. The risetime of the current pulse is therefore limited to that of the photometric trigger pulse. The other mode of device operation uses the avalanche-mode of a semiconductor to achieve high current gain with low light trigger levels, on the order of μJ. In this mode, charge is conducted by means of plasma-like filaments with high current densities in each filament, as predicted by the theory of current-controlled negative differential resistance[7]. Though in principle any semiconductor material can be made to function in either mode, most groups now fabricate linear mode devices of silicon, and avalanche mode devices from GaAs[8].

The comparative reliability of these two PCSS modes have been hypothesized based on their operative physics of conduction[9]. Based on evidence of filamentary conduction in avalanche mode devices, it has been suggested that these devices would not provide lifetimes as long as that of uniform conducting linear mode devices[10]. However, recent research has shown the presence of filamentary conduction even in linear-mode devices under certain conditions[11]. Still other related reports suggest that filaments may spontaneously increase in number during situations where the current density exceeds individual filament limits[12]. Reliability cannot be predicted by theory or related work -- it is the purpose of this paper to address the issue of avalanche mode PCSS reliability experimentally, and to show statistical data on the lifetime of one particular type of optically triggered avalanche-mode semiconductor switch - the Bulk Avalanche Semiconductor Switch (BASS)[13,14].

2. THEORY

The reliability engineering of solid state devices and of systems based on these devices has been well-established[15,16]. When accelerated life testing is not used, the salient features of solid state device reliability are straightforward. In review, there are three key definitions pertinent to such studies. These are :

1) Survivor Function S(t) or S(P): the fraction of devices which survive as a function of time, or pulses for the PCSS.

2) Cumulative Distribution Function F(t) or F(P): the fraction of devices which die as a function of time or pulses, F(t) = 1-S(t).

3) Hazard Rate $\lambda(t)$ or $\lambda(P)$: is the probability of failure in the next pulse, of devices which have survived to time **t** or pulse **P**. Mathematically, this is the rate of change of F(t) [called the *probability density function f(t)*] normalized by S(t). Mathematically,

$$\lambda(t) = \frac{[dF(t)/dt]}{S(t)} = f(t)/S(t) \tag{1}$$

$$S(t) = 1 - F(t) = \exp[-\int_0^t \lambda(t')dt'] \tag{2}$$

3.2 The Hazard Rate.

It is the Hazard Rate function, plotted on a log-log scale and shown in Figure 1, which should show the "bathtub" curve most clearly. The early part of the distribution function usually has a high slope, in which the failure rate of devices rapidly diminishes. This regime is often associated with the infant mortality regime of many semiconductor products. Usually, a nearly flat or gradually decreasing bottom of the Hazard Rate bathtub curve follows. Finally, the "wearout regime" appears in which the Hazard Rate rapidly increases with time or pulses, and all devices which have passed to this point fail due to some catastrophic material wearout mechanism. The general reliability model does not specify the nature of the failures or the wearout mechanisms -- further investigative work is required to determine the causes of failure. However, the reliability models do permit an understanding of the statistical nature of the failures. Merely specifying the maximum lifetime recorded does not describe the distribution. If all devices fail at nearly the same time, it indicates either wearout or significant infant mortality. If the devices failures decrease with time, it may indicates either a weak rate of infant mortality or the bottom of the bathtub curve, as Figure 1 illustrates.

In such a log-log Hazard rate versus Time graph, linear behavior indicates a Weibull data distribution. The Weibull distribution for the Hazard Rate has the form:

$$\lambda(t) = \lambda_0 \exp(-\alpha t) \tag{3}$$

Two forms of the Weibull distribution are generally found to describe the lifetime for most semiconductor devices. The infant mortality regime is usually fitted to a Weibull form. The bottom of the hazard rate is often observed to have α of zero, and in this special case of the Weibull distribution the form is called the exponential distribution[16]. Both cases are illustrated in Figure 1.

3. EXPERIMENTAL

Though the most desirable tests of any PCSS device reliability are those performed in the final system configuration, for several reasons a set of standard laboratory test conditions are needed. Due to complex interactions between the PCSS device and its electrical, optical, and thermal environments, it is impossible to determine the comparative quality of devices when tested differently. In many cases, final system assemblies are too costly to be suitable for rapid characterization.

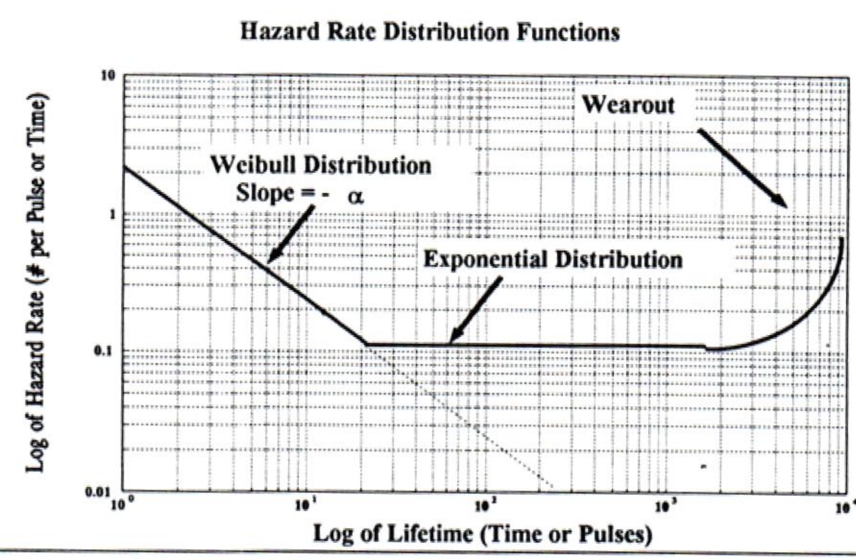
Further, the final assemblies may have terminations or impedances difficult to attach to RF diagnostic equipment. Therefore, what is needed is a combination of both systems level testing and other, more controlled laboratory assessments of BASS devices.

The BASS performance and diagnostic capabilities have evolved together over years of device development. The need for rapid, critical tests is important to ensure process consistency and materials quality. We have worked extensively to determine the most discriminating test methods. Although no one test can guarantee the success of the BASS or any other semiconductor device, the diagnostic tests included are those which can show inherent materials or processing flaws before devices are used in systems. In cases where the final configuration differs so substantially from the standard test conditions that the standard results cannot be correlated to final use, the standard test conditions must be changed. The characterization measurements described below are our best present set of diagnostics for the BASS; and our laboratory testing continues to evolve along with the systems employing these devices.

3.1 Equipment

To facilitate testing using standard diagnostic equipment, we have adopted a balanced 50-ohm Microstrip line Video Pulser test vehicle. The substrate is 1mm thick, 25.4mm wide and 76mm long, composed of high purity alumina. Centered on both sides are equivalent widths of Au-plated metal traces. The length of the input line is chosen to produce output pulses nearly 500ps wide. Ideally, output pulses are a single square wave with an output voltage equal to half the input charge voltage. To ease connection to the testing equipment, we attach a 0.1kΩ resistor at the input trace of the stripline and a 50-Ω SMA connector at the output. The entire assembly is encapsulated in suitable compounds to reduce corona degradation. Typically, the BASS is attached by either eutectic or conductive epoxy to the front of the output trace, and the mesa of the BASS is electrically attached to the input trace by either a metal tab or other means. Impedance mismatches and other non-ideal factors affect both the output amplitude and risetime, so all devices are assembled as identically as possible, or until assembly factors are experimentally proven to have no significant impact on the test results.

Figure 1: Bathtub curve. The hazard rate usually demonstrates three regimes -- Infant mortality, random mid-life failures, and wearout. After D. J. Klinger, Y. Nakada, M. A. Menendez, ref. 16.



Our testing is conducted under stringent experimental conditions. After the BASS is attached to its 50-Ohm Video Pulser test carrier, it is ready for installation in the pulse diagnostic test system. This test system is comprised of both mechanical and electrical components and electronic test gear. Mechanically, the Video Pulser is clipped onto a shielded thermoelectric heater/cooler, controlled to within 0.1C by an ILX Lightwave model LDT5910B under remote computer control. Thermally conductive paste is applied beneath the Video Pulser to ensure adequate heat transfer to the thermoelectric mounting of the test fixture. The 0.1kΩ input of the Video Pulser is attached in series to a high power 2kΩ resistor and then to the charging voltage output of a PSI model M610 High Voltage Modulator. A metal test chamber with tight-closing lid and safety interlocks encloses the HV Video Pulser. Ozone generated by the HV is actively pumped from the shielded chamber to a remote charcoal filter system.

Computer controlled optical and electrical pulses are applied and extracted from the shielded BASS Video Pulser. A Glassman HV model PS/PG 040R-025 ±40kV 25mA DC power supply, remotely programmed by a Keithley DAC-02 low voltage PC card, provides the HV input to a model M610 PSI Modulator. The M610 Modulator in turn generates pulses of up to 18kV and nearly 100ns risetime from the DC voltage. Output pulses from the BASS Video Pulser are attenuated 8000X by a string of 3 Barth Attenuators Models GLP26 (Attenuation of 20:1 Input/Output) in series. The final attenuator output connects to a Tektronix CSA803 sampling oscilloscope with an SD24 sampling head. The optical trigger pulses, adjusted to trigger the BASS at the peak of the voltage pulse, are provided by a proprietary PSI model LD100 Laser Driver unit. System electrical and optical pulses are synchronized by a HP model HP8112A Pulse generator and a PSI model FT100 Fine Timing Unit. All of the test equipment is interfaced to a 286 or 386SX computer via a National Instruments AT-GPIB bus. Specialized test programs were created at PSI to handle the instrument control, data acquisition, statistical analysis and data archiving.

3.2 Test Methodology for BASS wafers:

We assure that each BASS lot passes certain minimum criteria before further evaluation in advanced applications. The tests we perform can be classified as Visual, Parametric, Performance, and Reliability segments. The two forms of pre-electrical characterization, Visual and Parametric, are carried out to assure consistent qualities of BASS devices before extensive electrical testing is performed. All wafers must pass a FAB visual examination for gross defects, and are rejected if deemed unacceptable. Further visual examinations are performed by Assembly before acceptance for applications. On all lots, parametric R(V), I(T) and contact evaluation structures are measured. The R(V) and I(T) testing has been previously described[17], to determine the activation energy E_a @2kV, and the indicial points ($R_{maximum}$, Voltage at $R_{maximum}$, Voltage at 1 GΩ) of the R(V) curves. Each wafer also contains specific test patterns to permit estimates of the contact-related layer resistances, and the dimensional changes from lithographic and etching processes[18].

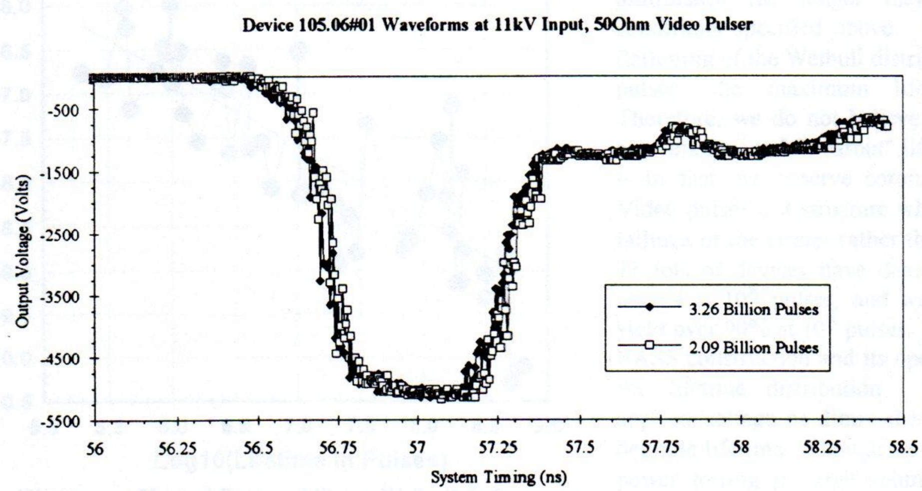


Figure 2: Typical Output waveform of BASS device in 50-Ohm Video Pulser. Note that at 3.3 Billion pulses, the measured waveform is indistinguishable from that measured at 2.1 Billion pulses.

After the preliminary testing is completed, Voltage Ramp diagnostics are taken in actual BASS pulse testing. First, 3 devices are optically triggered while the applied voltage is ramped in 500V increments from 2kV to 15kV, at 2kHz, 25C. The computer automatically shuts off the testing if the device fails below 15kV. Failure is determined by the condition in which the Output/Input voltage ratio (V_{ratio}) drops below a specified value. Diagnostics at each voltage level include Pulses Tested, Input and Output Voltages, Crossing Time, Jitter, 10-90% Risetime, and often Waveforms, are digitally stored. This testing provides parametric information about the BASS device efficiency, an indicator of the maximum operational voltage of a lot, and also the avalanche operation threshold voltage, which we define to be when V_{ratio} = 30%.

In Reliability, we typically test from 6 to 12 BASS devices for Lifetime at 8-10kHz, 25C, at 11kV to 14kV using Pulse charging. The computer automatically records the diagnostics at preset periods, and the Lifetime at which the BASS fails.

If the BASS passes to 10^7 pulses, it is preserved for possible further testing to 10^8 or higher pulses, as time permits. The characteristic lifetime of 1B pulses takes 1.44 days to acquire at 8kHz, making such testing prohibitively costly for routine lot analysis. An example of these diagnostics appears in Figure 5.

4. RESULTS AND ANALYSIS

4.1 Hazard Rate Distribution Function.

A reliability distribution function has not been demonstrated to date for PCSS Avalanche mode devices. Using standard methods of reliability testing to deduce the probability of failure, one must measure the lifetime of a population of similar devices. To establish the reliability distribution function experimentally, BASS devices have been measured under particular test conditions and evaluated. The measurements are taken using 11kV charging with a 100ns risetime charge pulse, 550ps BASS output pulsewidth, 50-Ohm input and output impedances, 2.1kOhm series chargeline resistance. The substrate is held at 25±0.1C, and testing is performed at 9±1kHz Pulse Repetition Frequency (PRF), triggered by 20±5W of optical power at 907±4nm by a quantum well laser having 5nsec pulsewidth. A typical output waveform is shown in Figure 2, which has waveforms taken with a single BASS device at 2.1 Billion and 3.3 Billion pulse diagnostic times. Note that aside from a slight shift in the overall system time scale, the two waveforms are identical.

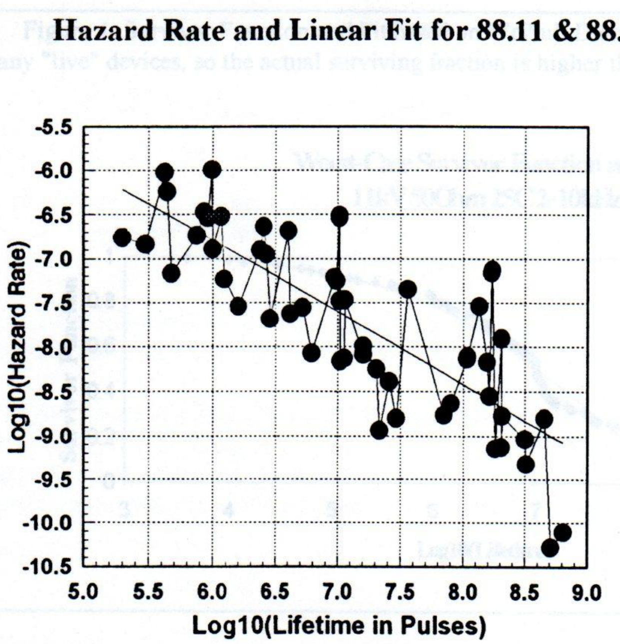


Figure 3: Worst-case Hazard Rate and linear Weibull fit for early process BASS devices. Not all of the data points represent failed devices.

Our lifetime data shows that BASS device hazard rate function follows a Weibull distribution. Figure 3 shows the Hazard Rate data for some early BASS processes. Though the data is noisy, it shows the cumulative Hazard Rate over many lots agrees closely with the Weibull distribution. In particular, the probability of failure of remaining BASS devices diminishes the longer they are tested under the conditions specified above. We have not observed a flattening of the Weibull distribution even out to 7 x 10^9 pulses, the maximum lifetime we have tested. Therefore, we do not believe that this level represents any fundamental "wearout" lifetime of the actual device -- in fact, we observe corona-induced damage of the Video pulser test structure which may be related to the failures of the circuit rather than the BASS itself. Over 11 lots of devices have demonstrated device lifetimes over 4 x 10^8 pulses, and we have had BASS wafers yield over 90% at 10^8 pulses. Various parameters of the BASS construction and its operating environment affect the lifetime distribution. For example, increased applied voltage or diminished video pulser impedance degrade lifetime. Though we have not established high power testing in large volume at this time, we have found lifetimes of nearly 2 x 10^8 pulses in 50-Ohm video pulsers at 13.5kV, and of 9 x 10^7 pulses at 11kV in 25-Ohm video pulsers. In each case, we find similar failure rate distributions as observed in 11kV, 50-Ohm circuits reported here. Using the established failure rate data, the device requirements for systems, and the need for suitable redundancy, can be assessed.

4.2 Fitting BASS lifetimes to a Weibull Hazard Rate Model.

For experimental reasons, there is a slight difference between the "standard" Weibull distribution function and the one we will use for BASS devices, as we are testing Pulses and not Time. Strictly speaking, we must take the survivor function S(t) to be 1 at t=0, or S(P)=1 at P=0, but there is a practical problem - at 10kHz the practical test time lower limit is about

10^5 pulses. Therefore, we transform the equations from the standard ones to appropriate ones for PCSS devices by taking the lower limit of the integral in equation (4) above to be non-zero, P_{min} pulses.

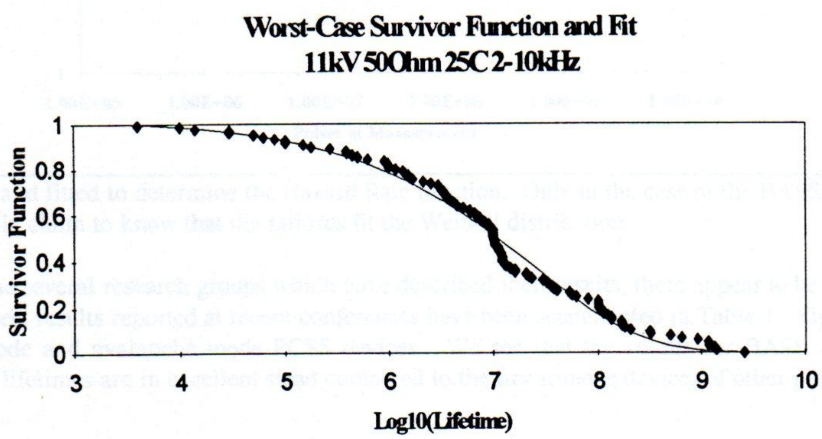
The survivor function can be also be fitted quite simply, using the slope of the Hazard rate function estimated from a least-squares linear fit. The Weibull model survivor function which we fit to our data with the coefficients α and λ to the equation explicitly becomes:

$$S(P) = \exp[-\int_{P\min}^{P} \lambda(t')dt'] \quad (4)$$

$$S(P) = \exp[-\int_{P_{min}}^{P} \lambda_1 P^{-\alpha} dP'] = \exp[-\frac{\lambda_1}{(1-\alpha)}\{P^{1-\alpha} - P_{min}^{1-\alpha}\}] \quad (5)$$

$$S(P) = \exp[-\frac{\lambda_1}{(1-\alpha)}\{P^{1-\alpha} - P_{min}^{1-\alpha}\}] \quad (6)$$

Figure 4: Survivor Function and Fit based on Weibull Distribution. This data includes many "live" devices, so the actual surviving fraction is higher than suggested by the fit.



The survivor function and its fit are shown in Figure 4. Once fitted, we can make predictions for device yields at various lifetimes, determine prescriptions for device screening, and estimate the reliability of systems employing numbers of BASS devices.

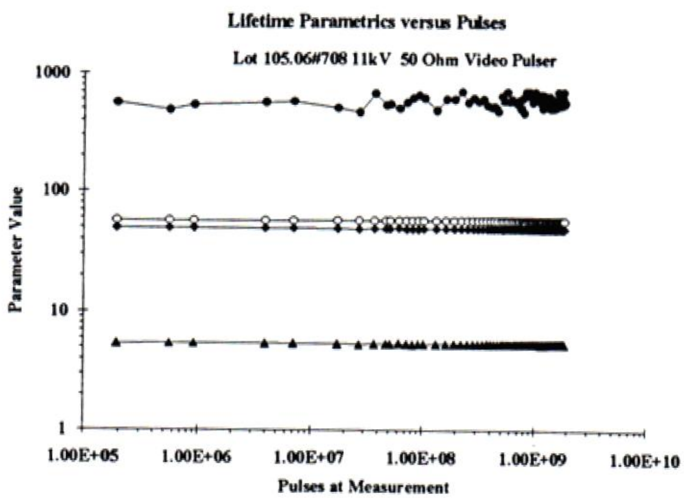
4.3 Changes in BASS Performance with Reliability Testing.

We have questioned whether there may be changes to the BASS performance which do not appear directly as lifetime. For example, there may be some degradation of the BASS risetime, crossing time, output voltage, or other measurable parameter which makes the device unusable before it or the circuit fails to operate. Though we have extensive data on this subject, it lies beyond the scope of this paper to incorporate it here. We have observed degradation of the output voltage of early-failure devices, but we have observed no such degradation in cases of long-lived devices. Non-destructive testing[17] of the BASS devices evidencing degradation in their output voltage showed that the Anode of the device was being affected by pulsing; the device cathodes were not affected. As Figure 5 shows, fluctuations in output voltage and crossing time are not generally seen over days, and when they occur are found to originate in system triggering fluctuations, not BASS device variations. The substrate temperature, trigger wavelength and intensity, voltage, impedance, material composition, and PRF have been shown to be significant factors affecting BASS performance and lifetime. These topics will the be subject of further reports.

4.4 Comparison to Earlier Studies

In situations where the maximum lifetime is reported, it is extremely difficult or impossible to assess the reliability of such devices in actual systems. That is because the nature of the failures must be shown statistically, to ensure that the quoted lifetime is not indicative of actual device wearout. In such cases where the lifetime is a wearout lifetime, the probability of failure before this lifetime cannot be assessed. For that to be deduced, a large quantity of similar devices must

Figure 5: Various Parametric Test Values versus Test Lifetime. Note that there is no significant variation in the BASS device up to the 2 Billion pulses to which it was tested.



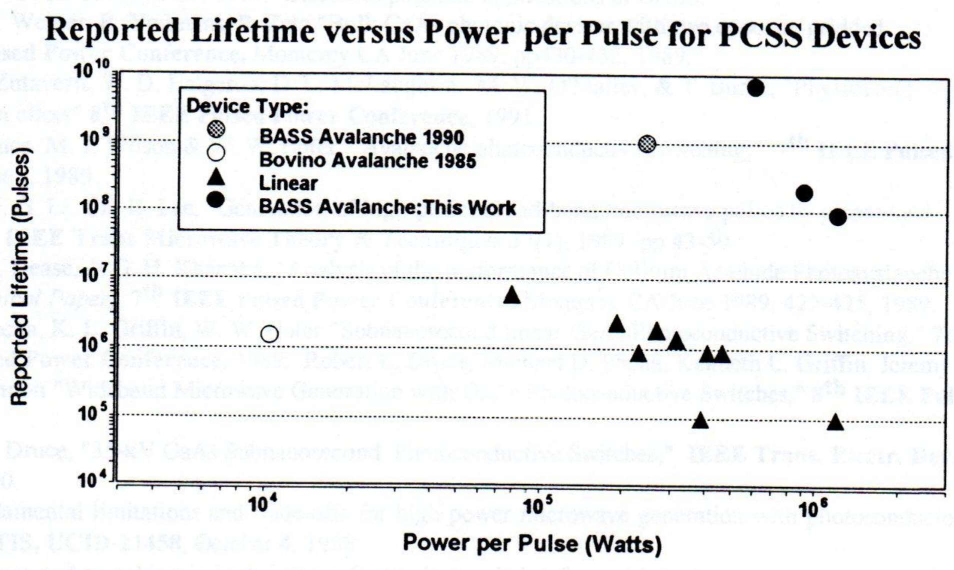
be tested and fitted to determine the Hazard Rate function. Only in the case of the BASS devices with recent processing can we actually claim to know that the failures fit the Weibull distribution.

Of the several research groups which have described their results, there appear to be a wide range of lifetimes observed. Various test results reported at recent conferences have been accumulated in Table 1. Figure 6 shows how data compare for linear mode and avalanche mode PCSS devices. We see that the results for BASS Avalanche mode device maximum achieved lifetimes are in excellent stead compared to the linear mode devices of other groups.

Table 1: Reported maximum lifetimes of various PCSS devices.

Mode - Semiconductor Material	Author	Year	Voltage In (kV)	Current Out (Amps)	Impedance (Ohms)	Power (MWatts per pulse)	Test Frequency (kHz)	Max Lifetime (Millions of Pulses)
Linear - GaAs	Druce[19]	1989					0.03	0.1
Linear - GaAs	Loubriel[20]	1990				1.2	1	0.1
Linear-Si	Denison[21]	1993	11	88	50	0.39	0.54?	0.1
Linear-Si	Denison	1993	10	79.5	50	0.32	0.54?	1.4
Linear-Si	Denison	1993	9	73.25	50	0.27	0.54?	1.9
Linear-Si	Denison	1993	8	62	50	0.19	0.54?	2.4
Linear-Si	Denison	1993	5.5	40	50	0.08	0.54?	6.0
Linear-Si	Denison	1993	12	96.5	50	0.46	0.54?	0.9
Linear-Si	Denison	1993	11	90.5	50	0.41	0.54?	22
Linear-Si	Denison	1993	8	68	50	0.23	0.54?	10
Avalanche-GaAs	Bovino[22]	1985	2	10.53	95	0.01	1	1.5
Avalanche-GaAs	Oicles[14]	1990	7	70	50	0.25	1	1000
Avalanche-GaAs	Herman, This Work	1993	11	110	50	0.60	10	7000
Avalanche-GaAs	Herman, This Work	1993	11	220	25	1.2	10	90
Avalanche-GaAs	Herman, This Work	1993	13.5	135	50	0.91	10	200

Figure 6: Comparison of reported lifetimes of Linear and Avalanche mode PCSS devices.



5. CONCLUSION

Though the factors affecting PCSS lifetime have been assessed by a variety of groups, none has shown the underlying reliability distribution function. It is therefore unclear whether the lifetimes reported are indicative of device technologies which can be extended, or whether they indicate some fundamental wearout mechanism. In the case of the BASS devices tested in 50-Ohm, 550ps video pulsers at 11kV, we find that the hazard rate follows the Weibull distribution. Further, from our waveform and diagnostic analyses we do not find evidence of fundamental device wearout in our present processes. Also, we detect no change in the slope of the Weibull (linear) fit of our BASS Hazard Rate data, suggesting that our best measured value of 7×10^9 pulses does not represent any fundamental limit to the BASS technology at this power level.

It is clear that the testing conditions of BASS devices must be intensified for several reasons. The lifetime of 1B pulses takes 1.44 days to acquire at 8kHz, exceeding our test time capabilities at 11kV in 50-ohm Video Pulsers. Furthermore, the systems in which BASS devices are used require more power from the BASS than this circuit provides. More stringent tests must be performed to assess the BASS in higher power systems and to achieve accelerated lifetime testing in the lab. To this end, we have decided to adopt higher power testing and establish its correlation to 50-Ohm Video results.

6. ACKNOWLEDGMENT

We would like to thank M. Gamble and S. C. Wessman for their review of the manuscript. The suggestions and support of Dr. R. A. Falk of the Boeing Company are gratefully acknowledged.

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