DC Drift Failure Rate Estimation on 10 Gb/s X-Cut Lithium Niobate Modulators

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***Abstract*—Application of the previously reported dc drift activation energy *Ea* = 1.4 eV to lifetime estimation on 10 Gb/s x-cut $LiNbO_3$ (LN) modulators is demonstrated. Notably, as the drifting bias voltage *V* (*t*) is proportional to the initially applied bias voltage *V* (0), it is proposed to determine the end-of-life criterion by the ratio *A* (*t*) = *V* (*t*) / *V* (0), independent of designed initial bias voltage of LN modulators and voltage limit of drivers. For instance, when the EOL is set at *A* (*t*) = 2 for 65 ℃ operation, the dc drift failure rate is calculated to be 300 failures-in-time from 120 ℃ accelerated biased aging data on 28 pieces of 10 Gb/s x-cut LN modulators.**

***Index Terms*—Activation energy, dc drift, failure rate, $LiNbO_3$ modulators.**

I. INTRODUCTION

WITH INCREASING demand for 10 Gb/s x-cut $LiNbO_3$ (LN) optical intensity modulators in global fiber communication systems, there is a necessity to know their reliability throughout 20 years of operation [1]. In this regard, the author reported previously the dc drift activation energy *Ea* = 1.4 eV on 10 Gb/s x-cut LN modulator with an SiO_2 buffer layer [2]. The purpose of this letter is to demonstrate the application of *Ea* = 1.4 eV to estimate the device failure rates induced by dc drift. Because the difference in long-term dc drift behavior between x-cut and z-cut LN modulators has not been investigated sufficiently yet, such a demonstration is believed to provide fruitful information to LN engineers. To the author's knowledge, concerning z-cut LN modulators, M. Seinio *et al.* of Fujitsu reported the dc drift failure rates calculated from 30 points of biased aging data at 100℃, 120℃, and 140℃, using their experimentally derived *Ea* = 1.4 – 1.6 eV [3].

Here, in order to increase usability of the results, bias voltages *V* (*t*) drifting with time *t* were normalized by the initially applied bias *V* (0), and the time dependency of the ratio *A* (*t*) = *V* (*t*) / *V* (0) was examined as discussed in the previous report on *Ea* [2]. Similarly, the end-of-life criterion was determined as $A(t)_{EOL} = V(t)_{max} / V(0)_{max}$, in which $V(t)_{max}$ denotes the maximum voltage limit of operation systems and $V(0)_{max}$ denotes the maximum bias voltage needed to adjust the operating point of modulator optical output before the operation. As a worst-case estimation, the $V(0)_{max}$ is assumed to be a summation of $V\pi$ and thermal drift voltage maxima of modulators; e.g. $V(0)_{max}$, is 6–8V for conventional x-cut LN modulators [4]. The thermal change of $V\pi$ is expected to be very small (<0.5 V) and may be omitted for the initial bias budget [5].

At first, the validity of the assumed equation *A* (*t*) = *V* (*t*) / *V* (0), i.e., the independency of the ratio *A* (*t*) on the initial bias voltage *V* (0), was examined using 12 hermetically sealed 10 Gb/s x-cut LN modulators. The dc drifts of these samples were measured twice at 85 ℃ by bias feedback control systems at λ = 1.55 μm. The initial bias voltage *V* (0) for the first measurement was set at 3.5 V for all samples, while the second initial bias *V* (0)' was set at a specific quadrature point of each optical modulation curve at 85 ℃. Measurement results are shown in Fig. 1, in which the vertical axis plots the second measurements *A* (63 hrs) at 85 ℃ normalized by *V* (0)', and the horizontal axis plots the first measurements *A* (63 hrs) at 85 ℃ normalized by *V* (0) = 3.5 V. The second initial bias voltages *V* (0)' applied to each sample are denoted in the graph. The data is seen to gather around a line corresponding to a 1 : 1 relationship, independent of magnitude and sign of the second initial bias voltage *V* (0)'. Thus, the equation *A* (*t*) = *V* (*t*) / *V* (0) is considered to be usable to process the dc drift data.

Fig. 2 shows 120 ℃ accelerated biased aging data on eight other samples prepared from different wafers. The applied voltage *V* (*t*) drifted chronologically from the initial bias voltage *V* (0) = 14 V as a result of dc drift. Because of highly accelerated conditioning by 120 ℃ heating, the rapid drift from the initial point was observed within the first hour. The cause of the observed difference in the drift profile is not completely known yet, and is suspected to de-

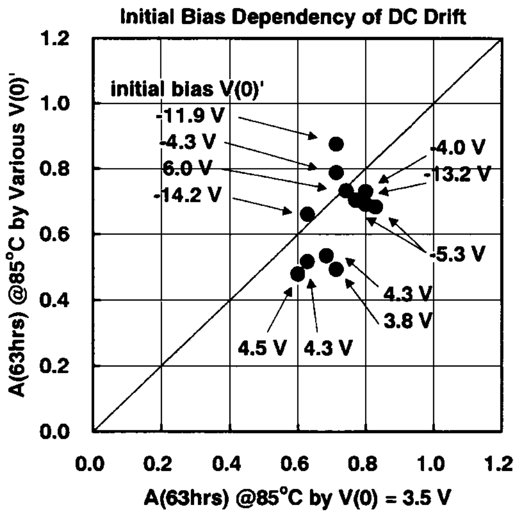

Fig. 1. A relationship between normalized voltage *A* (63 hrs) measured by initial bias voltages *V* (0)' = –14.2 to 6.0 V and constant initial bias voltage *V* (0) = 3.5 V on same modulator samples.

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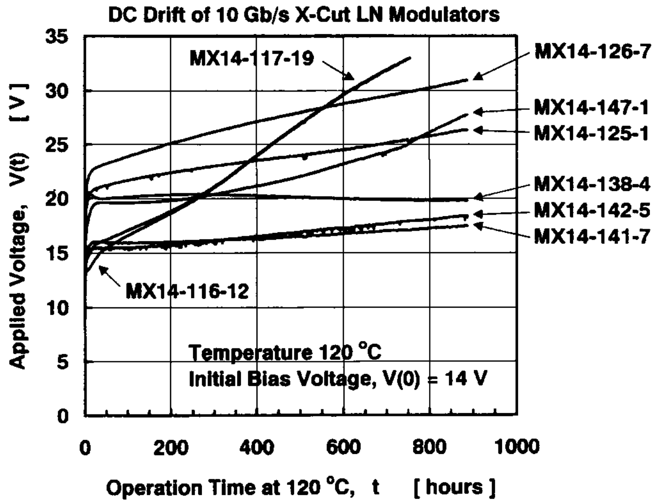

Fig. 2. 120 ℃ accelerated biased aging results.

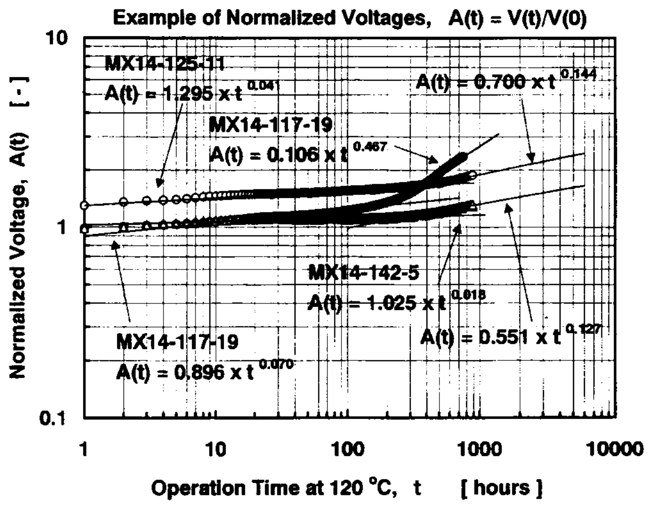

Fig. 3. Example of replotting of Fig. 2 data into time dependency of normalized voltage $A(t)$.

pend on a difference in fabrication lot of many SiO_2 buffer layers. For instance, two samples from neighboring wafer numbers MX 14-116 and -117 exhibited similar drift curves.

Fig. 3 is a replot of typical drift data of Fig. 2 as a relationship between $A(t)$ and t: samples MX14-117-19, MX14-125-11, and MX14-142-5. In order to express the drift curves simply, an equation of $A(t) = a \times t^n$ was used as successfully demonstrated in the previous report on Ea derivation [2]. Within a measured time range, the drift curve was found to be divided into two stages at a certain time depending on samples. The coefficient a and the index n of equations derived on 10-Gb/s x-cut modulator samples from 28 different wafers are listed in Table I. The measurements were performed at 120 ℃ for more than 300 hours, but the initial bias voltage $V(0)$ was altered (see Table I). A "kink point" denoted in the table means the time at which the first drift stage changed to the second stage. In most samples, this "kink point" was observed before the 200th hour at 120 ℃. For the failure-rate estimation, equations of the second drift stage were used, because 20 years at 65 ℃ (typical device operating conditions) corresponds to 210

TABLE I
EXPERIMENTALLY DERIVED DRIFT PARAMETERS

#	Samples Wafer No.	Samples Chip No.	Initial Bias [V]	1st Drift Stage $A(t) = a \times t^n$ a	1st Drift Stage n	Kink Point [hr]	2nd Drift Stage $A(t) = a \times t^n$ a	2nd Drift Stage n
1	MX14-98	21	6	-	-	-	0.889	0.125
2	MX14-104	25	6	0.897	0.047	10	0.775	0.102
3	MX14-107	3	6	1.241	0.039	30	0.883	0.135
4	MX14-108	11	6	1.153	0.051	100	0.594	0.191
5	MX14-116	12	14	0.783	0.093	200	0.103	0.472
6	MX14-117	19	14	0.896	0.070	200	0.106	0.467
7	MX14-125	11	14	1.295	0.041	300	0.700	0.144
8	MX14-126	7	14	1.382	0.049	100	0.767	0.155
9	MX14-138	4	14	-	-	-	1.401	0.007
10	MX14-139	4	6	-	-	-	1.588	0.025
11	MX14-141	7	14	1.071	0.014	400	0.624	0.102
12	MX14-142	5	14	1.025	0.018	100	0.551	0.127
13	MX14-147	1	14	1.251	0.025	500	0.035	0.595
14	MX51-14	22	11	0.927	0.048	100	0.213	0.357
15	MX51-24	24	7	0.662	0.141	40	0.974	0.044
16	MX51-29	25	11	0.788	0.039	200	0.416	0.157
17	MX51-30	16	11	0.917	0.031	60	0.542	0.142
18	MX51-38	7	11	0.975	0.014	400	0.196	0.273
19	MX51-39	20	11	0.895	0.019	300	0.351	0.184
20	MX51-49	17	-4.3	1.052	-0.020	10	0.737	0.105
21	MX51-51	20	9.7	1.048	0.095	20	1.336	0.016
22	MX51-60	3	4.8	-	-	-	1.014	0.079
23	MX51-73	26	4.7	1.010	0.106	50	1.392	0.020
24	MX51-75	26	3.7	1.084	-0.017	20	0.667	0.141
25	MX51-82	5	8.9	1.060	0.059	20	1.247	0.006
26	MX51-83	26	7	0.688	0.151	30	1.010	0.052
27	MX51-84	22	9.2	1.045	0.101	20	1.280	0.031
28	MX51-90	22	9.2	1.048	0.089	20	1.321	0.010

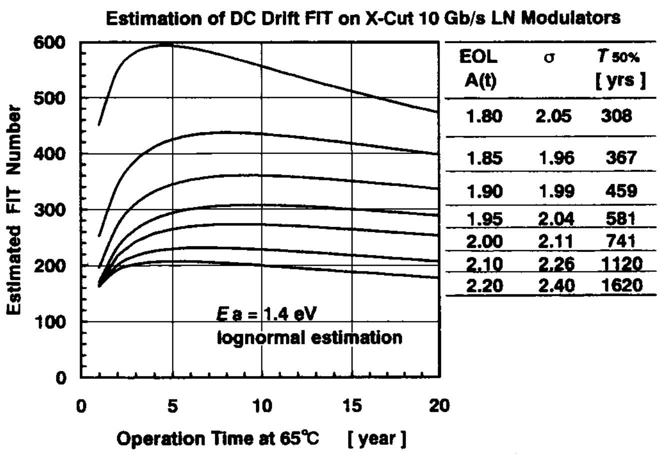

Fig. 4. DC drift failure rate estimation results.

hours at 120 ℃ when Ea = 1.4 eV.

The end-of-life (EOL) criterion for calculating failure rates was determined from the normalized voltage $A(t)_{EOL}$ using the maximum voltage limit of system drivers for $V(t)_{max}$ and the maximum initial dc bias expected to modulators for $V(0)_{max}$. Fig. 4 exhibits dc drift failure rates in failures-in-time (FIT) calculated using experimental data of Table I (2nd drift stage data) and a lognormal distribution function, in which EOL $A(t)_{EOL}$ was changed from 2.2 to 1.8, while the average operation temperature was fixed at 65 ℃. The Ea = 1.4 eV was used to convert the time axis at 120 ℃ (Table I) to the axis at 65 ℃. For instance, an $A(t)_{EOL}$ = 2.2 point t at 120 ℃ was calculated by substituting a

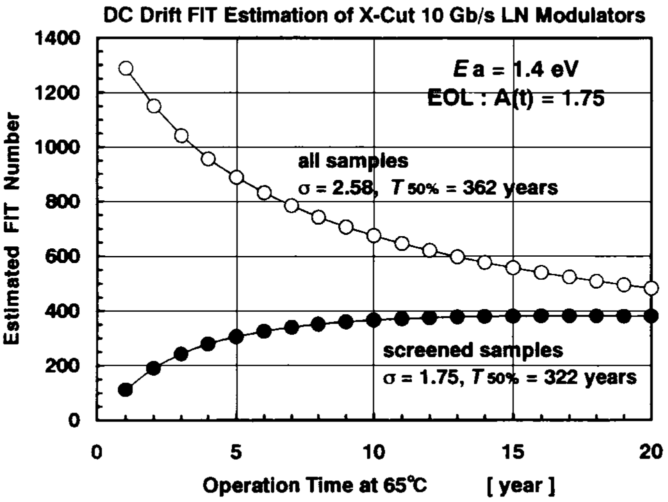

Fig. 5. DC drift failure rate estimation results on unscreened (white circles) and screened samples (black circles).

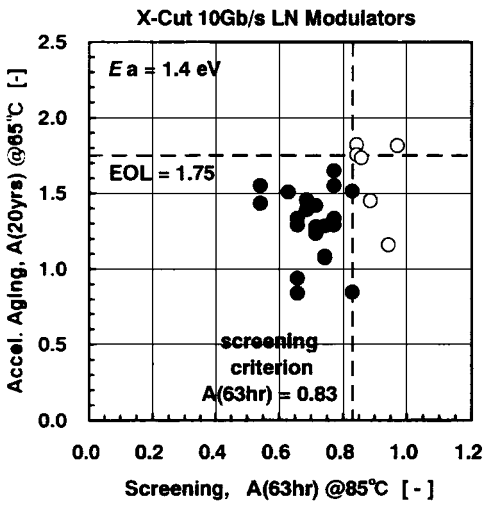

Fig. 6. A relationship between A (20 yrs) at 65 ℃ and screening results A (63 hrs) at 85 ℃. The white circles denote samples rejected by the screening to plot screened data of Fig. 5.

and n parameters of Table I into the equation $2.2 = a \times t^n$, and the obtained time t was converted to the EOL point t_{EOL} at 65 ℃ by $Ea = 1.4$ eV. Then, all t_{EOL} values calculated on 28 modulator samples were processed by lognormal distribution plotting [6] in order to find the distribution shape parameter σ and the median life $T_{50\%}$. According to the conventional method shown in Ref. [6], the inverse normal of cumulative distribution function (CDF) of failures calculated on 28 samples was plotted as a function of logarithmic t_{EOL} at 65 ℃. The gradient of plots and the CDF =50% points provide σ and $T_{50\%}$, respectively. The σ, $T_{50\%}$ and failure rate obtained for $A(t)_{EOL} = 2.2$–1.8 were denoted in Fig. 4, suggesting that the dc drift failure rate of 10 Gb/s x-cut LN modulators can be estimated to be less than 300 FIT's when the $A(t)_{EOL}$ is set at 2. The $A(t)_{EOL} = 2$ means that if the typical $V(0)_{max}$ is 6–8 V for conventional x-cut LN modulators within ordinary operating temperatures (0–80 ℃), the maximum drive-voltage $V(t)_{max}$ is to be expected at 12–16 V.

Fig. 5 reveals a failure rate estimation for further critical $A(t)_{EOL}$ assumed at 1.75; i.e. in a case of lower $V(t)_{max}$ and/or higher $V(0)_{max}$. The white circles exhibit the results estimated in a similar fashion to those of Fig. 4 using 28 data sets of Table I, showing large failure rates especially during the early stage of device operation. The results suggest that when the EOL criterion is set to be severe, many samples will drift over the criterion at an early stage of the operation: the infant-failures in dc drift performance. In this regard, a 100% screening process is commonly conducted for commercial LN. The black circles of Fig. 5 demonstrate the effect of screening test on samples of Table I; the infant-failures are completely waived. The screening test condition and criterion are shown in Fig. 6, in which data marked by white circles denotes samples rejected by the screening. The vertical axis plots A (20 yrs) values at 65 ℃ [equivalent to A (210 hrs) at 120 ℃] calculated on 28 samples of Table I, and the horizontal axis plots the screening results of the same samples measured before the 120 ℃ biased aging. The screening tests were done at 85 ℃ for 63 hours with the initial bias voltage of 3.5 V. For this demonstration, the ratio A (63 hrs) = 0.83 of screening tests was set as the criterion for EOL A (20 yrs) = 1.75. Further data accumulation is needed in order to discuss a validity of the screening criterion.

In conclusion, using $Ea = 1.4$ eV, the dc drift failure rates of 10 Gb/s x-cut LN modulators were estimated to be 300 FIT at 65 ℃ for the normalized voltage $A(t) = 2$ as the assumed EOL criterion. The effect of 100% screening tests was also demonstrated. Finally, the normalized voltage $A(t) = V(t) / V(0)$ was considered usable to determine EOL and screening criteria.

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